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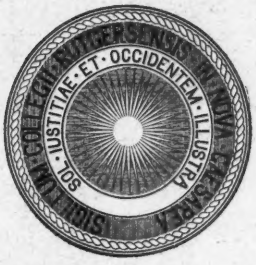

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SOIL SCIENCE

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SULFUR OXIDATION IN INOCULATED AND UNINOCULATED GREENSAND MIXTURES AND ITS RELATION TO THE AVAILABILITY OF POTASSIUM[1]

W. RUDOLFS[2]

New Jersey Agricultural Experiment Stations

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Although a study of the literature shows that the application of greensand for agricultural purposes has proved beneficial, and although good results from the use of greensand were recognised long ago in England and France and later in America, especially in New Jersey, farmers did not turn to these great resources even during the war-time scarcity of potassium. This is undoubtedly due to the fact that all greensands found in America have but a low percentage of potassium and to the ease with which the farmer in ordinary times can buy readily available potash.

The potassium of the greensand is but slowly available for plant food and the addition of greensand to a soil serves mainly the future crops. For building up a soil, poor in potassium, it has proven to be a great asset. The value of greensand as a fertilizer has been, and is still often ascribed to the calcium carbonate and phosphorus present. Since a large number of the New Jersey greensands contain from 1 to 3 per cent phosphoric acid and from 3 to 7 per cent potassium, it is probable that the immediately beneficial effects can be attributed to both these constituents. In many cases not much calcium carbonate is present and the greensand dug often has a decided acid reaction. The greensands and greensand marls found in England often contain as much as from 8 to 10 per cent of K_2O, but usually little or no phosphoric acid.

REVIEW OF LITERATURE

The war stimulated the study of practical methods for rendering the potassium soluble Experiments were conducted in several states upon the availability of greensands for plant food, and upon the possibilities of securing means to treat the greensand. The Eastern Potash Corporation in New Jersey (13) claims to have found a factory method which consists of treating the greensand with lime and steam under pressure, for which process a plant is under construction.

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[1] Paper No. 92 of the Journal series New Jersey Agricultural Experiment Stations, Department of Soil Chemistry and Bacteriology. This paper will appear in RUTGERS COLLEGE STUDIES, vol. 1.

[2] Part of a thesis submitted to the faculty of Rutgers College and the State University of New Jersey in partial fulfillment for the requirements of the degree of doctor of philosophy.

The writer wishes to express his thanks to Dr. J. G. Lipman for the suggestion of this problem and for the interest taken in the progress of the work.

Ashley (2) deems it entirely feasible to concentrate the glauconite by electric magnets, while his experiments with a solution of carbon di-oxide, sulfur di-oxide and dilute hydrochloric acid failed to give results of value for the production of commercial potash. A recently reported study at the Maryland Agriculture Experiment Station (9) shows the possibility of composting greensand with inoculated sulfur and manure as a practical means for farmers to make use of the potassium in the greensand.

A number of experiments have been conducted in different European countries with local greensand marls. In America the value of greensand has long been known. In 1819, at least four-fifths of the land in New Jersey around the places where the greensand marl is found, or two-fifths of the whole state was barren according to Morse's American Universal Geography (10). The analyses of the greensand made by Seybert (12) in 1822 shows the existing interest in these early days. A few years later Gordon (6, part 2, p. 5) wrote "It would be difficult to calculate the advantages which the state has gained, and will yet derive from the use of marl. It has already saved some districts from depopulation and increased the inhabitants of others, and may one day contribute to convert the sandy, and pine deserts into regions of agricultural wealth." The prediction of Gordon has come true and much of the land he considered as "deserts" are at present "regions of agricultural wealth." Cook (5) published in 1868 a geological report giving a large number of analyses of greensand samples. In his discussion he ascribes the heavy crops of clover, etc., to the beneficial effects of greensand partly because of the phosphoric acid content and partly because of the sulfuric acid found in it, for "this (sulfuric acid) constituent combines with lime forming plaster" of which the "efficiency as a fertilizer is well known, though the cause of its action is not satisfactorily explained." Although at that time the part played by potassium was not well understood, Cook points out that the peculiarly beneficial effects of greensand on potatoes containing high amounts of potassium, has strengthened the opinion that this constituent of the marl is of high value.

The most interesting greensand deposits of New Jersey and Maryland have been described by a number of writers. Clark (4), Ashley (2, p. 27–58) and others comment similarly on the value of greensand as a fertilizer. Patterson (11) concludes that the marls of Maryland have very little value for commercial extraction of the potassium on account of the great mass of worthless material in these shell marls. Blair (3) while reporting a number of analyses of New Jersey greensand samples concludes that, under the conditions existing in the soil, the potash of the greensand marls becomes gradually available, and since "potash is of especial value to potatoes and to grasses, the benefits derived from marl when used for these crops would lead one to believe that such crops can use the potash of marl to a considerable extent." Lipman and Blair (7) conducted experiments in pots with coarse sand growing barley and buckwheat followed by a crop of soy beans, using greensand as a source of potassium. Barley and buckwheat gave greatly increased yields over the check pots in these experiments. Soy beans fertilized with greensand produced as great a yield of hay as those receiving an application of soluble potassium salts. True and Geise (14) made a study of potassium salts and greensands in sand cultures, using Shive's complete nutrient solution, R_5C_2, as a basis. They conclude that "greensand and greensand marls from Virginia and New Jersey are able to supply sufficient potassium to satisfy the demands of Turkey Red wheat and red clover during the first two months of their growth. This enables them to make a greater dry weight of tops than was seen in similar cultures in which the potassium demand was supplied by potassium chloride, potassium sulfate, and potassium phosphate." Lipman and his co-workers (8) report field experiments with mixtures of greensand marl and inoculated sulfur. The greensand was applied together with acid phosphate and dried blood. The yields obtained with inoculated sulfur alone were as great as the returns from plots receiving a combination of greensand and inoculated sulfur, but the greensand alone compared with the uninoculated sulfur gave slightly greater yields, but the air dry weights produced by a combination of uninoculated sulfur and greensand was lower than the yields produced by either greensand or sulfur alone or a combination of these two constituents.

Ames and Boltz (1) report to have found that the oxidation of sulfur in the soil as well as dried blood liberated potassium. From these studies they conclude that the liberation of potassium was brought about by the salts rather than by the direct action of acidity on the insoluble potassium compounds. McCall and Smith (9) composted greensand with sulfur, soil and manure for the purpose of determining the effect of different composts upon the availability of the potassium of greensand. They inoculated the mixtures with a soil extract known to contain sulfur-oxidizing organisms and concluded, after an incubation period of 23 weeks, that "in composts consisting of greensand, manure, and soil in different proportions, an appreciable amount of potassium of the greensand was made water-soluble." Composts which yielded the largest quantities of water-soluble potassium contained the largest proportions of manure, indicating that nitrogen stimulates sulfur oxidizing bacterial activities.

PLAN OF EXPERIMENT

The experiments reported below were conducted primarily for the purpose of determining the effect of uninoculated sulfur as compared with inoculated sulfur upon the availability of potassium. In the second place the object was to study the possibility of decreasing the large quantities of soil used in earlier experiments, so as to make composting of greensand with sulfur more practical for the farmer or manufacturer, and in the third place to determine the effect of ammonium sulfate upon the rapidity with which the potassium ingreens and becomes available when no soil is used in the mixtures.

The experiments consisted of composting greensand with sulfur and soil in varying proportions and with additions of ammonium sulfate. Commercial sulfur and Penn loam were used. The greensand was from Eatontown, N. J., with a fairly high percentage of potassium and but a trace of calcium. Half of the mixtures were inoculated with infusions known to contain sulfur-oxidizing organisms, and to the other half no sulfur-oxidizing organisms were added. It was found extremely difficult to keep the uninoculated mixtures free from contamination. Although sterilized sulfur was used, much, if not all, of the soil around the New Jersey Experiment Station contains the sulfur-oxidizing organisms. The soil was left unsterilized so as not to change the soil flora, which would have resulted in placing some of the cultures at a too great disadvantage.

The materials were mixed in the following proportions:

COMPOST NUMBER	PARTS OF SOIL	PARTS OF SULFUR	PARTS OF GREENSAND	
1 and 9	100	20	80	
2 and 10	100	40	60	
3 and 11	20	20	160	
4 and 12	20	40	140	
5 and 13	0	20	180	
6 and 14	0	40	160	
7 and 15	0	20	180	0.2 per cent $(NH_4)_2SO_4$ added
8 and 16	0	40	160	0.2 per cent $(NH_4)_2SO_4$ added
9 and 18	0	0	200	

METHODS

All materials were air-dry and mixed thoroughly before the inoculations were made and before the ammonium sulfate was added. A part of each mixture was used for determining the water-holding capacity, Hilgard method. Water equivalent to 60 per cent of the water-holding capacity was then added to the mixtures and they were left standing over night before determinations of hydrogen-ion concentration, relative acidity, sulfates and potassium were made. The cultures were placed in tumblers covered with glassplates and incubated at 28°C.

Water extractions were made of weighed air-dried samples from each compost by shaking 20 gm. of mixture with 200 cc. of distilled water in 1-liter flasks in a shaking machine for 2 hours. The flasks were left standing over night and an aliquot drawn off from each for the pH determinations. The remainder of the contents of the flasks was then filtered until the liquid was clear.

The hydrogen-ion concentrations were at first determined according to the method described by Gillespie and later checked up with a portion of the liquid drawn off after shaking of the mixture with distilled water. The differences,

TABLE 1

Composition of greensand and soil used

	MOISTURE	INSOLUBLE RESIDUE	Fe_2O_3 Al_2O_3 MgO Na_2O	K_2O	P_2O_5	CaO	SO_4	pH
	per cent	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
Greensand	3.54	54.11	30.79	4.53	1.16	Trace	1.08	6.5
Penn loam	2.17	76.04	12.49	0.49	0.17	0.32	0.52	6.7

if any, were always very slight. As indicators, the series recommended by Clark and Lubs was used with the apparatus described by Van Alstine (15).

Determinations of relative acidity were made upon aliquots of the water extract. The liquid was boiled to expel carbon dioxide, cooled, and titrated with 0.1 *N* NaOH, using phenolphthalein as an indicator.

Potassium determinations were made gravimetrically at the platanic chloride method from aliquots of the water extract. The silicates, iron, aluminum, phosphorus and soluble organic matter were eliminated by evaporation with H_2SO_4, ignition and subsequent precipitation with NH_4OH.

The soluble sulfur was determined by acidifying aliquots of the water extract with concentrated hydrochloric acid and precipitating at the boiling point with barium chloride. The results are calculated as sulfur trioxide (SO_3).

The results recorded are calculated on the moisture-free basis of the soil and greensand. Moisture determinations being made by heating portions of air-dry material and composts for 15 hours at 105° to 108°C.

The greensand and soil were analysed by the official methods at the beginning of the investigation. The results are reported in table 1.

From the hydrogen-ion concentration determinations it may be seen that both soil and greensand were slightly acid. The greensand was rather coarse and therefore crushed in a mortar before mixing with the soil. Mechanical analyses of the greensand and Penn loam used, showing their texture, are given in table 2.

TABLE 2

Mechanical analyses of greensand and soil used

CONSTANTS	GREENSAND	PENN LOAM
	per cent	*per cent*
Fine gravel	0.42	6.75
Coarse sand	18.64	23.92
Fine sand	42.75	26.25
Very fine sand	29.20	26.56
Silt and clay	8.63	16.32

EXPERIMENTAL RESULTS

Acidity and hydrogen-ion concentration

The acidity and hydrogen-ion concentration of the water extracts from each compost were determined at intervals of the inoculated and the uninoculated mixtures. Part of the data obtained are reported in table 3.

It is clear from the data presented that no great differences were found between the cultures with inoculated and uninoculated sulfur. As has been pointed out this was to be expected since it is extremely difficult to keep the inoculated mixtures from contamination under ordinary laboratory conditions. All cultures showed a rapid change in hydrogen-ion concentration and a gradual increase in titratable acidity. After 6 weeks one of the cultures to which soil was added had reached the point of hydrogen-ion concentration at which the potassium of the greensand becomes available, which point was reached by most of the cultures after an incubation period of 9 weeks. From then on the hydrogen-ion concentration changed but slightly, although acidity accumulation went on, showing that sulfur oxidation proceeded. These slight changes in hydrogen-ion concentration indicate that but relatively small amounts of free acid existed and nearly all of the acidity titrated existed in the form of sulfates. The mixtures with soil made somewhat larger quantities of acidity, from the beginning but the intensity of the acid produced was generally less than in the cultures without soil. The quantities of acidity titrated were highest in the mixtures with 50 per cent soil. Addition of ammonium sulfate did not seem to have much influence upon the quantity of acid produced, nor upon the intensity of the acid produced except, possibly, as shown by some slight differences in the uninoculated cultures between those receiving neither soil nor ammonium sulfate and those receiving ammonium sulfate but without soil. There seemed to be sufficient nitrogen available for the needs of the organisms to last until the end of the experiment.

TABLE 3

Accumulation of water-soluble acidity, hydrogen-ion concentration, water-soluble sulfate, and water-soluble in potassium inoculated and uninoculated compost mixtures

NUMBER	COMPOSITION			INITIAL REACTION		REACTION AFTER 18 WEEKS		SO_3 PER 10 GM. OF COMPOST				K PER 10 GM. OF COMPOST	
	Soil	Sulfur	Greensand					At start	After 9 weeks	After 15 weeks	After 18 weeks	At start	After 18 weeks
Inoculated													
	parts	*parts*	*parts*	*cc.**	*pH*	*cc.**	*pH*	*mgm.*	*mgm.*	*mgm.*	*mgm.*	*mgm.*	*mgm.*
1	100	20	80	0.05	6.6	37.6	2.3	1.32	200.24	218.99	233.08	1.24	7.91
2	100	40	60	0.05	6.6	42.0	2.2	1.30	186.74	211.25	228.66	1.08	7.39
3	20	20	160	0.05	6.6	26.8	2.2	1.48	158.22	184.96	200.85	0.72	11.79
4	20	40	140	0.05	6.6	31.2	2.0	1.48	184.99	204.89	206.92	0.56	12.68
5	0	20	180	0.06	6.6	29.6	2.0	1.70	161.16	207.47	212.07	0.62	16.48
6	0	40	160	0.08	6.6	25.8	2.0	1.68	114.58	164.81	184.47	0.53	11.47
7	0†	20	180	0.10	6.6	24.0	2.1	3.72	147.50	184.60	198.89	0.36	12.71
8	0†	40	160	0.08	6.6	30.0	2.0	3.40	150.18	193.92	215.27	0.20	11.71
17	0	0	200	0.10	6.5	0.1	6.3	1.08	6.60	7.90	8.02	0.25	0.29
Uninoculated													
9	100	20	80	0.05	6.6	31.2	2.2	1.32	101.66	145.44	197.86	0.54	7.23
10	100	40	60	0.05	6.6	38.2	2.4	1.30	163.74	192.35	218.15	0.82	6.07
11	20	20	160	0.05	6.6	24.2	2.1	1.48	146.92	161.99	179.14	0.27	11.07
12	20	40	140	0.05	6.6	31.4	2.1	1.48	173.01	184.43	199.92	0.45	11.31
13	0	20	180	0.06	6.6	19.3	2.3	1.70	101.02	141.54	170.77	0.15	12.27
14	0	40	160	0.08	6.6	17.2	2.3	1.68	113.85	159.17	149.55	0.27	11.31
15	0†	20	180	0.09	6.6	27.0	2.2	3.72	142.19	158.52	192.40	0.18	13.80
16	0†	40	160	0.08	6.6	22.8	2.3	3.40	130.95	182.62	190.86	0.18	12.18
18	0	0	200	0.10	6.5	0.1	6.2	1.08	6.58	7.22	8.83	0.25	0.36

*Acidity expressed in cc. 0.10 norm. NaOH required to neutralize acidity of water extract of 10 grams compost.

†0.2 per cent ammonium sulfate added.

SULFATE FORMATION

The production of water-soluble sulfates during the first weeks of incubation was very rapid in all mixtures. From the results recorded in table 3 it may be seen that after an incubation period of 15 weeks the inoculated mixtures had produced more sulfates than the uninoculted composts.

This gain, however, was largely lost after 18 weeks, due to the fact that the sulfate accumulation was slow between the 9th and 18th weeks of incubation. The reason for the slower accumulation may possibly be that the sulfates and free acid formed at first do not react with the mineral constituents present, or do so only very slightly, but when sufficient amounts are produced a comparatively rapid reaction takes place with the extremely small particles, while later on the slower reaction takes place with the more coarse material. In the course of this process a part of the sulfates unite with bases of the silicates and become insoluble in water. The more rapid attack of small particles would

indicate that finely ground greensand yields greater amounts of the water soluble potassium. An experiment conducted with material of different fineness showed distinctly that the finer material used, the faster the reaction takes place. No attempt was made to study the possible interchange of bases in this relatively slow reaction process.

WATER-SOLUBLE POTASSIUM

Water-soluble potassium determinations were made at the beginning of the experiment, after 1, 3, 6, 9, 15 and 18 weeks. The data secured after 18 weeks are recorded in table 3.

The increase in water-soluble potassium was gradual in all cultures. The amounts during the first 12 weeks were small.

Until the fifteenth week the inoculated cultures were ahead of the uninoculated, but after 18 weeks not much difference was apparent. The possible reason has been pointed out by the discussion of the accumulation of water soluble sulfates.

The total water-soluble potassium seemed to be greatest in all mixtures without soil additions, but if calculated on the basis of the per cent of total potassium present, this is reversed.

It is necessary that a certain degree of acidity be produced before the potassium becomes water-soluble. The amounts of sulfates formed do not necessarily have to reach a certain quantity, but the acidity produced has to be of a certain intensity. The point at which the potassium of the greensand becomes more rapidly water soluble lies between the pH values 2.7 and 2.3, as is shown by determination made from greensand extracts treated with dilute sulfuric acid. Nevertheless, the quantities of sulfates formed have a close relation to the intensity of the free acid formed.

The curves in figure 1, show clearly the relation between hydrogen-ion concentration, acidity accumulation, sulfate formation and water-soluble potassium in two of the inoculated mixtures.

It seems evident that a part of the acid or acid sulfates formed in culture 1 reacted with the soil constituents, while in culture 3 these sulfates or the free acid acted more directly upon the potassium of the greensand. It would seem that most rapid and thus most economical results would be obtained if a part of the composts were used for inoculaton of new compost mixtures, eliminating thereby the long period of incubation before a certain hydrogen-ion concentration and a certain acidity accumulation is reached.

As has been pointed out above, the total water-soluble potassium seemed to be greatest in all mixtures containing no soil, but from the data presented in table 4 it is evident that a smaller percentage of the total potassium present had been liberated in the cultures without additions of soil. It should be kept in mind that the greensand contained but 4.63 per cent of total potassium and much of the materials present react with the acid or acid compounds formed. Besides, the reaction was not complete and still continuing at the end of 18

weeks. Since only a small amount of the sulfur was oxidized it does not seem necessary to add such large quantities of sulfur as was done in this experiment. The cultures to which 40 gm. of sulfur were added had accumulated almost

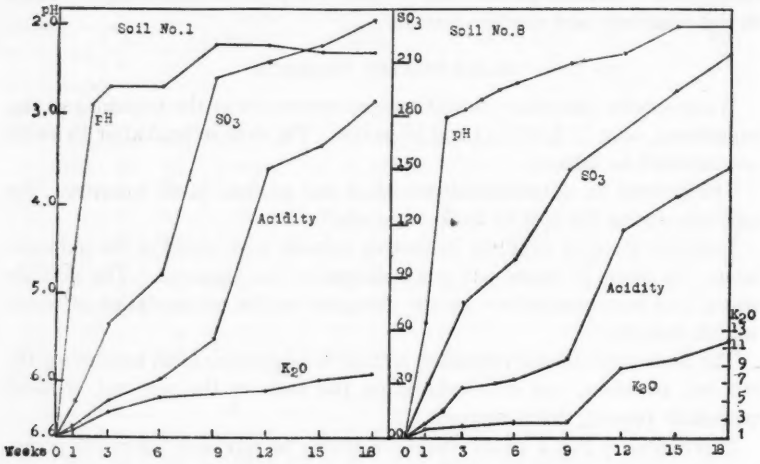

FIG. 1. GRAPHS SHOWING THE RELATION BETWEEN HYDROGEN-ION CONCENTRATION SULFATES, ACIDITY AND WATER SOLUBLE POTASSIUM IN COMPOST MIXTURES NUMBERS 1 AND 8

TABLE 4

Total sulfur oxidized and total water-soluble potassium obtained

CULTURE NUMBER	SULFUR IN MIXTURE	SULFUR OXIDIZED		POTASSIUM K_2O IN MIXTURE	SOLUBLE POTASSIUM	
	gm.	*gm.*	*per cent*	*gm.*	*gm.*	*per cent*
1	20	1.864	9.32	3.624	0.1582	4.37
2	40	1.830	4.57	2.718	0.1478	5.44
3	20	1.606	8.03	7.248	0.2358	3.26
4	40	1.658	4.14	6.342	0.2536	3.99
5	20	1.698	8.49	8.154	0.3296	4.04
6	40	1.474	3.68	7.248	0.2294	3.17
7	20	1.592	7.96	8.154	0.2542	3.12
8	40	1.723	4.31	7.248	0.2342	3.23
9	20	1.578	7.89	3.624	0.1446	3.92
10	40	1.746	4.36	2.718	0.1214	4.47
11	20	1.442	7.21	7.248	0.2214	3.07
12	40	1.588	3.97	6.342	0.2262	3.57
13	20	1.369	6.85	8.154	0.2454	3.01
14	40	1.196	2.99	7.248	0.2262	3.13
15	20	1.540	7.70	8.154	0.2760	3.38
16	40	1.528	3.82	7.248	0.2435	3.36
17	None			9.06	0.0007	0.078
18	None			9.06	0.0006	0.067

exactly the same amount of sulfates as the culture to which 20 gm. of sulfur were added. The relation between the percent of potassium liberated and the per cent of sulfur oxidized was roughly 1:2. It seems therefore, that approximately 10 per cent of sulfur of the total greensand is sufficient to secure satisfactory yields.

SAND CULTURES

The per cent of water-soluble potassium was low in all cases, but it seemed sufficient to supply plants with the necessary amounts of potassium. In order to test whether or not the available potassium would be sufficient to support plants with this necessary plant food element, pot cultures were conducted with soy bean plants. Since, as has been shown by earlier investigations, potassium absorption is greatest during the first part of the growing period of the plants, soy beans were grown for only 6 weeks. Soy bean plants ordinarily bloom in the greenhouse between the fourth and fifth week and the growing period of 6 weeks would be enough to test the value of the material for these plants.

Although it is known that the ordinary glazed earthenware pots furnish very small amounts of soluble impurities among which are potassium compounds, it was thought that the differences among the cultures would be large enough to give this test practical value. As a source of the necessary nutrient salts Shive's cultural solution R_5C_2 was used.

Each pot contained 5 kgm. washed quartz sand. Treatments, in triplicate series were as follows:

1. None
2. Dry greensand.
3. Shives cultural solution R_5C_2.
4. Composted greensand.
5. Shive's solution, except potassium, plus dry greensand.
6. Shive's solution, except potassium, plus composted greensand.

The greensand substituted for the potassium in Shive's cultural solution was calculated to be approximately that necessary to supply an amount of potassium equivalent to that in the solution. The inoculated greensand had been composted for a period of 18 weeks previous to the application. The results from the plants grown in these cultures would thus be comparable with the sults of the plants grown in cultures with the easily available potassium of Shive's cultural solution.

The soy bean seeds were selected for size and germinated in sand. The seedlings were then selected again to be as nearly alike as possible and planted when about two inches high. After the planting the cultures were inoculated with a few cc. of a water extract known to contain nodule forming bacteria. The yields obtained after a growing period of 6 weeks are presented in table 5 in the form of dry weights of tops, height of plants, number of pods produced, and the pH values at the beginning and at the end of the experiment.

It will be noted that the dry greensand alone had some influence on the growth of these soy bean plants.

The dry greensand substituted for the potassium in the cultural solution was apparently not able to replace the potassium fully for the needs of these plants in this period of growth, but the composted greensand seemed to render sufficient potassium available for their needs. In fact, the cultures receiving greensand as a substitute matured earlier and seemed more vigorous than the plants in Shive's nutrient solution.

From the numbers of pods produced, it can be seen that the plants receiving greensand as a substitute for the potassium in Shive's solution would yield also more seeds, showing that their earlier maturity was profitable instead of detrimental, although slightly less hay was produced as compared with the plants grown in the R_5C_2 solution. In addition, more and larger nodules were noticed on the roots of all plants receiving potassium in the form of greensand.

TABLE 5

Yields of tops of soy beans grown in sand cultures, with Shive's nutrient solution as a basis, with the potassium of the solution replaced by the potassium of composted greensand

CULTURE NUMBER	TREATMENT	DRY WEIGHTS OF TOPS	AVERAGE HEIGHT	NUMBER OF PODS	REACTION		NODULES
					Initial	Final	
		gm.*	cm.		pH	pH	
1	None	0.856	8	Bloom	5.7	6.8	Small
2	Greensand	1.132	9	2	5.3	6.1	Large
3	R_4C_2	3.356	14	4	5.4	6.4	Few
4	Composted greensand	1.206	8.5	2	5.4	5.8	Abundant
5	R_5C_2, greensand	2.501	13	6	5.0	6.5	Few, but large
6	R_5C_2, composted greensand	3.299	14	9	4.8	6.4	Few, but large

* All results given are averages of 3 cultures.

CONCLUSIONS

1. In composts consisting of greensand and sulfur, small amounts of potassium are liberated.

2. No great differences occured between inoculated and uninoculated sulfur-greensand mixtures, because there was contamination of the uninoculated mixtures.

3. The potassium of the greensand is made available at a certain hydrogen-ion concentration, lying between the pH values 2.7 and 2.3.

4. There is a definite relation between the hydrogen-ion concentration and sulfate formation, and the water-soluble potassium.

5. Soy bean plants grown in quartz sand and with Shive's nutrient solution in which composted greensand was substituted for the potassium of the cultural solution are able to make as great a dry weight of tops as in similar cultures in which the potassium was supplied in the form of potassium phosphate.

Soy bean plants receiving composted greensand as a source of potassium matured earlier and yielded more seeds than the plants grown in Shive's cultural solution.

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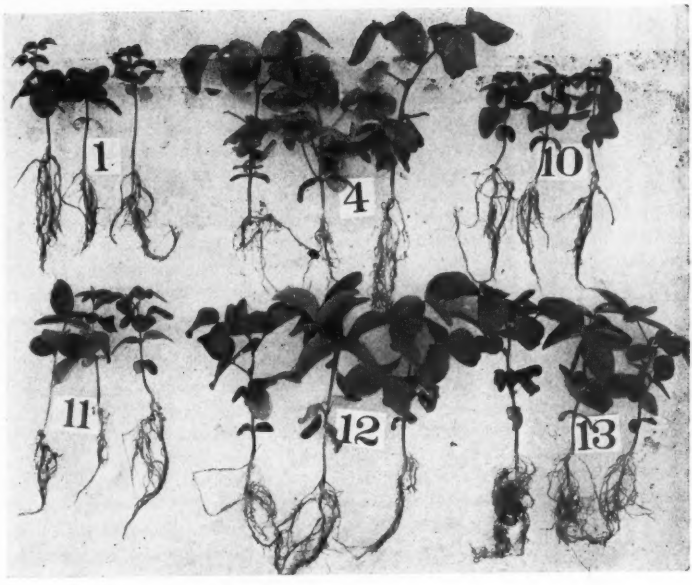
PLATE 1

SOY BEAN PLANTS GROWN IN QUARTZ SAND TREATED AS FOLLOWS

1. None.
4. R_5C_2.
10. Composted greensand.
11. Greensand.
12. R_5C_2 and composted greensand.
13. R_5C_2 and greensand.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MICROBIOLOGICAL ANALYSIS OF SOIL AS AN INDEX OF SOIL FERTILITY: III. INFLUENCE OF FERTILIZATION UPON NUMBERS OF MICROÖRGANISMS IN THE SOIL.[1]

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HISTORICAL

The majority of the earlier investigators on the numbers of bacteria in the soil including Remy, Hiltner and Störmer, Löhnis, Kruger and Heinze, Brown, Conn, etc., have concerned themselves very little with making a direct practical application of their investigations to actual soil conditions. These investigations led merely to establishing the fact that numbers of microörganisms in the soil are more or less uniform [although even this is questionable, as pointed out in the first paper of this series (16)], that the application of stable manure and green manure increase the number of microörganisms in the soil, that continued drying or treatment with volatile antiseptics has a depressing effect, and subsequent moistening of the soil has a stimulating effect. Engberding (2) found the number of bacteria in the soil to run parallel with the moisture-content of the soil and Fabricius and Feilitzen (3) found a parallelism with soil temperature.

Rahn (14) found that the crop and the system of cropping exert a direct influence upon the numbers of microörganisms but Engberding (2) has shown that, whenever a difference was observed due to cropping, it could be accounted for by the moisture content of the soil. Hiltner and Störmer (7) found that fallowing resulted in a decrease in numbers, but Krüger and Heinze (8) obtained an increase. The addition of organic matter, in the form of dextrose, straw and green manure results, according to Engberding (2), in a large increase in numbers, followed by a decrease, so that in a few months the level of the control is reached. Ammonium sulfate, sodium nitrate, potassium sulfate, lime and magnesium were found by Engberding to have a slight stimulating effect upon numbers of microörganisms in the soil, while superphosphate was without influence.

A detail review of the earlier investigations on the subject is found in the Handbuch of Löhnis (11).

Only in very few instances has there been an actual attempt made to correlate numbers of microörganisms in the soil with crop production. In most cases the results have been rather negative. This has been due to the fact that usually few, unrepresentative soil samples have been used, and to the fact that the methods have not been standardized, so that the results obtained, even when positive, were so variable as to be of questionable importance. The desirability of a correlation between the information obtained from the study of bacterial activities and crop production has been pointed out by Fischer (4).

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[2] The author wishes to thank Mr. J. S. Joffe and Mr. R. L. Starkey for assistance in the taking of the samples and in pouring the plates, and Dr. J. G. Lipman and Prof. A. W. Blair for permission of using the plots and data for the productivity and history of plots.

In a few cases, however, definite correlations have been obtained between the number of microörganisms and soil productivity, but, unfortunately, these observations have been rather sporadic and not followed up in a systematic way. Neller (12), for example, obtained a noticeable correlation between crop yield, oxidizing power of the soil, nitrate production and bacterial numbers, but not between crop yield and ammonia accumulation, thus foreshadowing the reliability of the three first bacteriological functions and the unreliability of the ammonia-producing power of a soil as an index of its fertility. A definite correlation between bacterial numbers and crop yield has also been recorded by Noyes and Conner (13) and others.

EXPERIMENTAL

In the two previous papers in this series, the important principles to be observed in the study of numbers of microörganisms in the soil have been discussed. This paper deals with the influence of soil fertilization upon the numbers of microörganisms.

Before making an extensive study of the numbers of microörganisms in the soil, some information had to be obtained on the condition of equilibrium in the soil and on the variability of microörganisms in various soil samples kept under the same conditions. For that purpose a greenhouse soil was air-dried, 600-gm. portions were placed in each of six small, glazed earthenware pots, and enough water added to bring it to 70 per cent of the moisture-holding capacity of the soil (28 per cent). The soil was stirred every 7–10 days, with the addition, at those intervals, of the proper amount of water to keep the soil at constant moisture. Three of the pots were left untreated, and, to three pots 22.5 mgm. of sulfur and 90 mgm. of rock phosphate were added. The numbers of microörganisms exclusive of fungi, were determined at various intervals and the results are given as averages in table 1 and figure 1.

When the soil is air-dried, there is a sudden drop in the number of microorganisms to one-half the number of the fresh soil, which we would expect due to the sudden elimination of many of the non spore-forming bacteria. When the soil is again moistened, there is a rapid increase in bacterial numbers, reaching not only the original value, but increasing to more than double. This is due to the influence of drying upon the soil, which served as a stimulus of the bacterial activities in the soil. The increase in numbers is somewhat uneven in the different pots (see table). The rise in numbers continues till the second sampling which took place two weeks later, and is then followed by a fall in numbers.

We thus find a rapid rise in numbers, due to the effect of drying which lasts for a short period of time and followed by a drop. The drop is not so sudden as the rise, indicating that the numbers come again only slowly to a new equilibrium. Since the stimulus was not due to the introduction of new food material, but merely to a change in the soil condition, we would expect that the new equilibrium once established will be at a lower plane than the first one. The stimulated activity of microörganisms will result in a decomposition of the soil organic matter which will leave the soil poorer than it was before and thus

TABLE 1

*The course of change of numbers of microörganisms in the soil**

DATE	SOIL CONDITION	COLONIES (IN THOUSANDS) PER GRAM OF SOIL						
		1a	1b	1c	2a	2b	2c	Average
1/ 7/21	Fresh soil	21,750†						21,750
1/21/21	Air-dried soil	10,700†						10,700
1/25/21	Soil was moistened on 1/21/21	44,260	35,320	50,590	49,680	34,330	47,880	43,677
2/ 8/21	Moist	49,210	37,210	49,320	46,610	38,660	37,580	43,098
2/25/21	Moist	33,240	37,220	38,750	25,840	29,630	25,840	31,753
3/18/21	Moist	23,680	21,330	16,700	26,534	26,070	24,470	23,131
4/13/21	Moist	21,660	19,130	15,060	26,000	23,000	22,200	21,175
5/13/21	Moist	16,000		9,200				12,600
7/ 8/21	Moist	13,000	11,360	5,400	8,200	8,800	8,600	9,227
12/12/21	Moist	5,600	4,800	4,600	4,700	5,200	5,600	5,083

* 1a, 1b, 1c are the pots containing only soil; 2a, 2b, 2c contain, in addition to 600 gm. of soil, 22.5 mgm. sulfur and 90 mgm. rock phosphate. Numbers represent all the colonies, except fungi, in thousands per gram, on the basis of soil dried to constant weight.

† These figures represent the averages of the uniform soil previous to distribution in the pots.

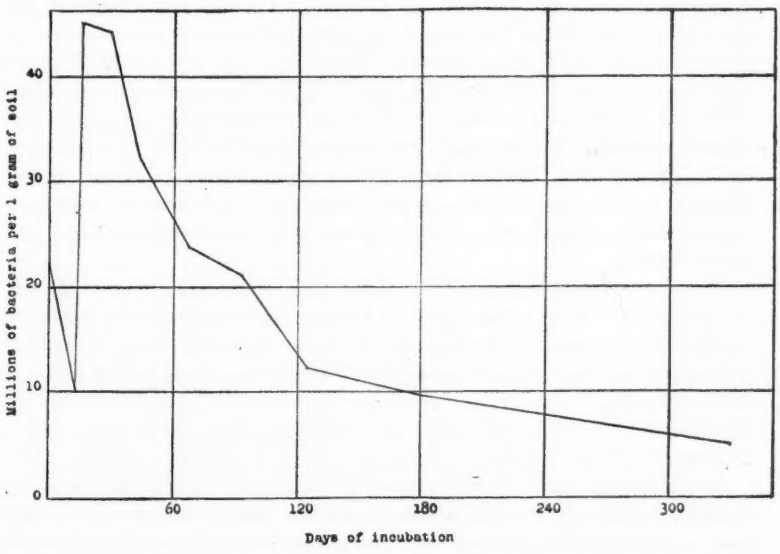

FIG. 1. COURSE OF NUMBERS OF MICRÖORGANISMS IN SOIL PLACED IN CONTAINER AND KEPT IN THE LABORATORY AT UNIFORM MOISTURE CONTENT

able to harbor fewer microörganisms. With each repeated stimulus (shift of the unstable equilibrium), if no other nutrients in the form of nitrogenous fertilizers or organic matter are added, there will result a new equilibrium at a lower stage than the previous one. This will parallel the phenomena of unproductivity of a constantly fertilized soil.

It is interesting to note that on July 8, only six months after the soil had been taken from the greenhouse, air-dired, and again moistened, the numbers dropped to a level as low or lower than that in the original air-dried soil. It is also of interest to note that pot 1c, in which the bacterial numbers reached the highest peak, dropped down to the lowest point in numbers, while the pots 2a, 2b and 2c, which had an addition of phosphate, fell down to a lower level than pots 1a and 1b. This would suggest a solution of the problem, based not upon toxin production, activities of protozoa, or any other theory adapted at one time or another to explain this common soil phenomenon, but a mere principle based upon physico-chemical laws, namely that of mass action and equilibrium. This subject is of so great importance that merely to touch upon it is to overlook its part in soil microbiological activities. It will be the subject of one of the following papers in this series. A detailed study of the influence of air drying upon the bacteriological activites in the soil is found in the papers of Rahn (14) and Heinze (6).

For the study of the influence of fertilization upon the numbers of microorganisms in the soil, a series of plots, used by the Soil Department of the New Jersey Agricultural Experiment Stations for the study of availability of nitrogenous fertilizers were selected. These plots are one-twentieth of an acre in size and were laid out in 1908; since then they have been under the same system of fertilization, one-half of the plots receiving various fertilizer and manure treatments without lime, the other receiving the same treatment and lime. The soil is a Sassafras loam with a small amount of coarse gravel. The crop rotation used consists of corn, oats, wheat, and timothy, with some supplementary residual crops. When these studies were made, the plots were under timothy.

These plot experiments, as well as the results of chemical analysis of the soil, are described in detail in the papers of Lipman and Blair (9, 10) in which the crop yields obtained for the first ten years, are reported. Only those data will be reported here which have a direct bearing upon the problem at hand. Of the 20 unlimed and 20 limed plots, ten were selected, namely 4A, 5A, 7A, 9A, 11A, 18A, 19A, 7B, 11B, 19B. The following tables give a description of fertilizer treatment, composition and crop yields for the plots selected.

It will be noted that the highest crop yields were given by Plot 18A receiving manure, sodium nitrate and minerals, and 5A, the plot that received manure alone, in addition to minerals. Next to the two manured plots came the two plots receiving minerals, ammonium sulfate and lime (11B) and sodium nitrate (9A).

TABLE 2

Fertilizer treatment and carbon and nitrogen content of plots

PLOT NUMBER	FERTILIZER TREATMENT ON ACRE BASIS	TOTAL CARBON*		TOTAL NITROGEN	
		1913	1917	1913	1917
		per cent	*per cent*	*per cent*	*per cent*
4A	Minerals only (640 lbs. acid phosphate and 320 lbs. potassium chloride)	1.36	1.26	0.1180	0.1088
5A	Minerals and 16 tons of cow manure	1.38	1.44	0.1002	0.1185
7A	Nothing	0.95	0.93	0.0790	0.0785
9A	Minerals and 320 lbs. $NaNO_3$	1.15	1.13	0.0921	0.0975
11A	Minerals and $(NH_4)_2SO_4$ equivalent to 320 lbs. $NaNO_3$	1.14	1.21	0.0977	0.0904
18A	Minerals and 16 tons of cow manure and 320 lbs. $NaNO_3$	1.47	1.36	0.1088	0.1170
19A	Minerals only (same as 4A)	1.29	1.01	0.0980	0.0872
7B	Same as 7A, with lime†	1.17	1.02	0.0879	0.0821
11B	Same as 11A, with lime†	1.02	1.06	0.0801	0.0819
19B	Same as 19A, with lime†	1.11	0.95	0.0809	0.0784

* The average of analysis of 5 plots in 1908 when the plots were laid out gave 1.22 per cent of carbon and 0.1118 per cent of nitrogen.

† The fertilizer treatment of the B plots is the same as of the corresponding A plots, with the addition of 1 ton of ground limestone per acre in 1908, 2 tons in 1913 and 2 tons in 1918.

TABLE 3

*Yield of dry matter for the years 1908–1921**

PLOT NUMBER	TOTAL FOR 5 YEARS 1908–1912	TOTAL FOR 5 YEARS 1913–1917	TOTAL FOR YEARS 1918 AND 1920†	YIELD FOR 1921‡	TOTAL FOR 13 YEARS
	lbs.	*lbs.*	*lbs.*	*lbs.*	*lbs.*
4A	13,874	8,800	5,964	1,270	29,908
5A	26,119	21,130	9,322	3,970	60,541
7A	7,352	3,950	3,842	151	15,295
9A	21,879	17,745	7,984	2,880	50,488
11A	21,595	12,805	2,161	2,170§	38,731
18A	29,362	23,140	10,584	4,340	67,426
19A	13,305	7,610	5,442	870	27,227
7B	11,645	9,145	5,799	650	27,239
11B	22,018	19,110	9,078	3,620	53,826
19B	12,098	10,440	7,264	1,650	31,452

* Total of dry matter (hay, straw, grain) is given as pounds per acre.

† Heavy rainfalls delayed the harvesting of the crop of 1919 causing heavy loss of the grain; the results for that year are, therefore, rather misleading, and are for that reason left out entirely.

‡ Pounds of hay per acre.

§ The second crop, on this plot, amounting to 1720 pounds per acre, consisted entirely of crab grass; the actual yield of timothy, on this plot, was only 450 pounds per acre.

TABLE 4

*Numbers of microörganisms in the soil on May 20, 1921**

4A			5A			7A			9A			11A			18A			19A			7B			11B			19B		
B+A	A	F	B+A	A	F	B+A	A	F	B+A	A	F	B+A	A	F	B+A	A	F	B+A	A	F	B+A	A	F	B+A	A	F	B+A	A	F
49*	2	4	196	41	2	36	13	1	98	21	0	19	2	6	136	33	3	56	17	1	79	24	3	82	21	1	119	21	2
78	9	3	198	28	6	46	18	3	74	17	4	35	3	7	143	38	3	51	12	1	96	23	0	78	17	1	112	29	3
109	12	3	181	32	2	42	12	1	108	26	0	25	3	5	152	42	2	64	12	3	71	19	3	107	33	1	111	33	0
69	8	5	145	36	7	33	10	3	106	20	2	34	4	4	122	31	3	56	10	3	79	18	2	108	22	2	120	28	2
46	6	3	152	23	3	45	16	1	92	23	2	27	6	4	131	28	1	36	9	3	95	28	1	96	26	1	134	32	0
78	4	2	168	35	5	37	10	4	121	28	1	24	6	5	143	36	3	71	16	3	83	23	0	103	24	0	136	31	3
53	6	3	169	26	4	53	17	3	97	22	1	23	4	3	146	27	2	78	12	0	82	29	0	83	28	2	121	28	1
84	15	1	178	24	2	46	9	1	108	19	1	40	8	1				50	16	2	93	24	2	111	27	0	122	24	0
71	7	3	247	32	3	41	12	2	68	14	2	18	6	3				59	14	2	96	23	3	92	18	1	114	25	2
54	4	3	224	39	3	45	12	2	92	32	1	39	9	1							98	24	2	102	30	3	124	34	2
69	14	2	153	23	3	61	16	1	115	23	4	32	3	5	156	31	2	54	8	2	95	29	1	106	24	1	125	27	1
81	19	2	146	19	5	45	12	2	104	19	2	47	3	5	168*	41	3	102	13	2	86	32	2	90	22	1	98	28	2
74	8	3	144	24	3	58	14	2	78	13	2	32	2	3	156	32	3	56	11	3	104	36	5	104	26	1	85	26	2
65	11	0	143	28	5	53	15	1	112	24	2	38	2	5	166	36	2	61	17	3	85	26	0	112	29	2	81	24	2
64	10	2	148	23	4	46	13	3	129	32	3	24	1	7	178	42	3	98	27	2	64	21	2	132	31	0	98	37	2
75	9	3	131	21	3	51	8	6	133	23	0	33	8	9	148	30	2	46	8	3	88	28	1	116	29	1	106	32	2
77	8	3	143	24	3	61	16	1	105	28	2	21	4	4	196	32	3	85	22	1	78	24	3	88	18	2	116	34	0
66	9	0	122	18	6	46	12	2	97	24	4	17	2	5	163	26	2	115	19	3	84	24	1	91	24	1	103	35	2
75	17	4	128	18	3				128	18	2	29	2	7				68	16	2	91	26	0	132	24	2	129	33	2
54	7	4	107	17	4							14	4	3										158	32	3	102	32	1
104	18	4	84	17	3	48	14	3	98	16	1	22	0	4	94	22	2	65	16	1	72	18	2	107	26	1	116	29	1
58	6	2	102	23	2	59	18	1	132	22	3	36	3	5	122	35	2	62	22	2	76	25	2	92	24	2	109	29	2
51	4	2	58	6	4	59	11	6	111	13	4	12	2	8	116	37	2	51	12	4	93	37	3	91	17	2	118	28	1
86	6	1	62	9	2	51	15	2	139	15	1	24	2	3	128	39	4	62	16	2	78	19	0	92	16	2	126	30	2

*The numbers in tables 4–12 indicate the total number of colonies developing on the plate. The actual number will be obtained by multiplying by the proper dilution (100,000 for B and A and 1000 for F).

53	8	1	47	7	5	39	6	1	146	14	1	22	3	6	138	49	2	47	11	6	66	12	2	118	20	1	148	42	0
86	12	1	124	23	3	39	10	4	133	12	2	10	2	3	126	32	2	61	15	4	86	24	2	120	32	0	151	41	2
73	7	2	77	20	3	46	9	2	105	5	1	13	3	6	136	31	3	72	21	1	79	22	3	121	37	2	142	32	1
75	11	3	105	21	4	52	12	0	91	7	1	19	2	7	142	41	2				81	18	2	86	19	2	180	41	1
																					82	23	0	86	17	2	122	31	2
																								94	16	1	119	38	3
66	8	2	93	29	4	41	15	2	67	4	1	18	3	7	191	32	2	41	11	1	69	13	2	122	26	3	122	32	2
89	7	3	128	38	5	48	16	3	85	9	0	28	3	4	152	31	1	36	13	1	53	16	2	156	31	2	132	32	2
76	4	3	72	19	3	52	20	2	82	7	1	45	5	3	163	37	1	73	16	1	86	19	1	112	29	2	136	33	1
68	10	4	87	22	3	38	20	2	93	9	1	42	6	8	136	26	2	53	13	1	68	21	2	116	23	5	128	34	2
74	8	2	102	31	5	46	15	0	99	13	2	41	3	2	178	38	2	64	13	3	88	23	2	113	22	2	105	28	2
102	12	5	98	28	3	39	13	2	103	18	1	31	4	5	164	28	5	69	15	2	73	21	0	149	26	1	102	29	1
117	11	2	142	36	6	37	16	3	71	7	2	28	2	4	157	38	2	52	10	4	78	22	0	96	19	2	136	30	1
88	14	5	68	26	3	51	17	6	64	6	1	32	2	6	182	27	2				71	23	2	107	33	2	142	28	0
																					69	15	2				132	32	2
																					58	16	2				113	22	2
105	13	2	112	26	4	54	16	3	109	22	1	33	4	3				69	19	3	46	13	1	68	19	4	182	46	3
83	9	2	116	24	2	47	10	1	71	18	3	32	6	3				56	14	2	68	23	0	79	26	3	108	32	0
78	12	3	84	17	3	31	13	5	102	25	0	18	2	4				78	16	4	66	26	0	69	22	1	109	26	3
53	6	3	83	18	4	62	18	6	77	20	1	42	11	4				70	14	2	88	23	0	90	23	1	152	29	1
98	8	3	97	26	3	58	20	2	76	15	2	32	8	2				67	18	5	73	31	1	61	14	3	148	29	3
92	8	4	88	21	4	43	9	2	88	17	0	23	7	8				44	9	3	68	17	0	85	28	4	165	27	3
62	7	3	108	18	5	45	13	1	81	24	5	12	2	0				38	11	4	69	18	3	76	19	4	132	35	3
68	9	1	118	22	5	36	8	1	106	22	3	37	2	4				89	19	2				65	18	3			
			123	26	2																								
			127	21	2																								

The poorest yields were obtained from the unfertilized plot (7A) followed by those that received either lime alone (7B) or minerals alone (4A and 19A). The plot receiving ammonium sulfate alone gave rather good yields the first 5 years, but gradually dropped down due to increasing acidity from the yearly application of the fertilizer, as seen from table 13 where the reactions are given.

The plots were sampled 4 times throughout the summer, May 20, June 27, July 18, and September 22. The first set of samples was taken when the soil had not yet had a chance to dry out, the second set of samples was taken after a prolonged dry spell, and the third and fourth soon after brief heavy rainfalls, at the end of dry periods. Fifteen to twenty individual samples were taken from different parts of each plot by means of a 1-inch sampling tube from the upper 6 inches of soil and mixed into 5 composite samples which were used for the determinations, except on June 27 when only 4 samples were prepared for each plot.

The methods of sampling, plating, etc., were given in the previous paper (17). The moisture content and soil reaction (5, 1) at the various dates of sampling are found in the summary table 13. By mistake, the soil moisture was determined only roughly in the first set of samples.

Tables 4, 5, 6, 7, 8, 9, 10, 11 and 12 contain the numbers of microörganisms obtained, by the plate method, on the different dates of sampling. The first four tables (4, 5, 6, 7) contain all the microörganisms developing on the albumen agar plate; the three columns for each plot have the following designations: B + A = bacteria and actinomycetes, indicating all the organisms developing on the plate, except the fungi; A = actinomycetes; F = fungi. Tables 8, 9, 10, 11 contain the numbers of microörganisms, except the fungi found on July 18, 1921 and September 22; the fungi for the samples taken on the corresponding dates were determined by the use of the special acid medium (17) having a pH = 4.0 with a dilution of 1:1000, and are briefly summarized in table 12.

The dilutions used in counting the total number of microörganisms were in all cases 100,000. The figures designate the number of colonies on the plate. The plates were always incubated 3 days for the special fungus media and 7 days for the bacteria and actinomycetes at 25–27°C. The total number of microörganisms per gram of moist soil can then be obtained by merely multiplying the number of colonies by 100,000. By making another multiplication by a factor allowing for the moisture content of the sample, as given in table 13, the numbers are obtained on the basis of air-dried soil. 10 plates (8–9 plates for table 9) were poured for each soil sample using synthetic agar (modified albumen). At first all the colonies, except the fungi, were counted, with the naked eye and reported under column B + A. The actinomycetes were then counted and reported under A, while the fungus colonies are given under F. Where plates were badly overgrown with fungi, particularly in the case of certain *Mucorales* which prevent any extensive development of bacteria and actinomycetes, the plates were discarded and not included in the count. Each

TABLE 5

Summary of results reported in table 4

PLOT NUMBER	MEAN			σ			C.V.			Em		
	B+A	A	F	B+A	A	F	B+A	A	F	B+A	A	F
	colonies	*colonies*	*colonies*				*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
4A	74.9 ± 1.7	9.2 ± 0.4	2.6 ± 0.12	17.0 ± 1.2	3.7 ± 0.4	1.2 ± .09	22.7 ± 1.6	40.6 ± 4.6	46.1 ± 3.5	2.3	4.1	4.6
5A	124.5 ± 4.6	23.2 ± 0.76	3.7 ± 0.12	46.8 ± 1.5	7.7 ± 0.6	1.25 ± .09	37.6 ± 1.2	33.2 ± 2.6	33.8 ± 2.4	3.7	3.2	3.3
7A	46.8 ± 0.85	13.6 ± 0.36	2.4 ± 0.16	8.15 ± 0.59	3.5 ± 0.26	1.6 ± .17	17.4 ± 1.3	25.8 ± 1.9	65.8 ± 7.1	1.8	2.6	6.7
9A	99.9 ± 2.15	17.8 ± 0.75	1.7 ± 0.13	20.96 ± 1.52	7.3 ± 0.53	1.55 ± .11	21.0 ± 1.5	41.0 ± 3.0	91.2 ± 6.5	2.15	4.2	7.6
11A	27.8 ± 0.98	3.8 ± 0.24	4.6 ± 0.21	9.6 ± 1.02	2.42 ± 0.34	2.04 ± .31	34.5 ± 3.6	63.7 ± 8.9	44.3 ± 6.7	3.5	6.3	4.6
18A	149.3 ± 2.78	33.8 ± 0.72	2.4 ± 0.10	22.96 ± 2.9	6.0 ± 0.76	0.84 ± .07	15.4 ± 2.0	17.8 ± 2.2	35.0 ± 2.9	1.86	2.1	4.2
19A	63.1 ± 1.85	14.6 ± 0.44	2.41 ± 0.13	17.4 ± 1.3	4.18 ± 0.32	1.26 ± .09	27.6 ± 2.06	28.6 ± 2.2	52.5 ± 4.6	2.9	3.0	5.4
7B	79.0 ± 1.22	22.6 ± 0.55	1.5 ± 0.12	12.2 ± 0.9	5.53 ± 0.39	1.2 ± .23	15.4 ± 1.1	24.5 ± 1.70	80.0 ± 15.3	1.5	2.4	8.0
11B	101.4 ± 2.20	24.1 ± 0.54	1.8 ± 0.11	22.16 ± 1.55	5.49 ± 0.38	1.13 ± .08	21.8 ± 1.5	22.8 ± 1.6	62.8 ± 4.4	2.17	2.24	6.1
19B	124.1 ± 2.07	31.0 ± 0.50	1.6 ± 0.09	21.14 ± 1.46	5.16 ± 0.36	0.94 ± .07	17.2 ± 1.2	16.6 ± 1.2	58.8 ± 4.4	1.66	1.6	5.6

TABLE 7

Summary of results reported in table 6

PLOT NUMBER	MEAN			σ			C.V.			Em		
	B+A	A	F	B+A	A	F	B+A	A	F	B+A	A	F
	colonies	*colonies*	*colonies*				*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
4A	47.0 ± 1.03	12.9 ± 0.35	2.0 ± 0.13	9.6 ± 0.72	3.28 ± 0.25	1.25 ± 0.09	20.4 ± 1.5	25.4 ± 1.9	62.5 ± 4.5	2.2	2.7	6.5
5A	60.6 ± 1.43	18.1 ± 0.73	3.0 ± 0.23	13.27 ± 1.01	6.85 ± 0.52	2.22 ± 0.17	21.9 ± 1.6	37.8 ± 2.9	74.0 ± 5.7	2.36	4.0	7.7
7A	36.1 ± 0.99	9.4 ± 0.26	2.0 ± 0.20	9.32 ± 0.70	2.48 ± 0.19	1.85 ± 0.13	25.8 ± 1.9	26.4 ± 2.0	92.5 ± 6.5	2.7	2.77	10.0
9A	66.5 ± 1.3	20.3 ± 0.63	1.6 ± 0.12	12.15 ± 0.91	5.95 ± 0.45	1.17 ± 0.09	18.3 ± 1.3	29.3 ± 2.2	73.1 ± 5.6	1.95	3.1	7.5
11A	15.6 ± 0.57	2.3 ± 0.16	4.3 ± 0.29	5.41 ± 0.41	1.54 ± 0.11	2.72 ± 0.21	34.7 ± 2.6	67.0 ± 4.8	63.3 ± 4.9	3.65	7.0	6.7
18A	128.0 ± 3.5	29.7 ± 0.83	3.0 ± 0.2	32.8 ± 2.5	7.76 ± 0.59	1.84 ± 0.14	25.6 ± 2.0	26.1 ± 2.0	61.3 ± 4.7	2.0	2.8	6.7
19A	40.1 ± 1.14	11.9 ± 0.49	2.0 ± 0.17	9.7 ± 0.8	4.19 ± 0.35	1.46 ± 0.12	24.2 ± 2.0	35.2 ± 2.9	69.5 ± 5.7	2.8	4.1	8.1
7B	50.9 ± 1.23	20.3 ± 0.7	1.2 ± 0.12	10.83 ± 0.88	6.13 ± 0.5	1.04 ± 0.08	21.3 ± 1.7	30.2 ± 2.4	86.7 ± 6.7	2.4	3.45	10.0
11B	77.1 ± 3.53	20.6 ± 0.67	1.3 ± 0.14	30.63 ± 2.51	5.85 ± 0.48	1.25 ± 0.10	39.7 ± 3.2	28.4 ± 2.3	96.2 ± 7.7	4.6	3.25	10.8
19B	73.0 ± 1.79	23.0 ± 0.46	1.6 ± 0.17	16.4 ± 1.26	4.22 ± 0.33	1.52 ± 0.11	22.4 ± 1.7	18.3 ± 1.4	95.0 ± 6.9	2.45	2.0	10.6

TABLE 6

*Numbers of microörganisms in the soil on June 27, 1921**

4A			5A			7A			9A			11A			18A			19A			7B			11B			19B		
B+A	A	F	B+A	A	F	B+A	A	F	B+A	A	F	B+A	A	F	B+A	A	F	B+A	A	F	B+A	A	F	B+A	A	F	B+A	A	F
42*	9	4	82	28	3	39	7	3	53	16	2	18	6	5	112	29	3	47	11	3	61	25	0	67	17	1	50	13	2
46	12	0	76	20	3	41	7	1	58	25	2	18	6	3	82	18	4	43	13	1	47	16	1	82	19	0	59	22	1
47	14	1	66	21	4	41	12	3	68	21	4	16	2	2	96	19	7	54	19	3	36	16	1	76	25	0	51	25	0
38	12	4	52	22	4	46	12	2	58	18	4	8	1	2	82	18	3	52	14	2	55	29	1	67	21	0	55	23	4
47	11	2	83	28	2	39	14	0	62	26	2	13	3	2	95	21	4	36	7	4	54	28	0	53	15	2	64	19	7
53	13	0	76	36	0	35	12	3	86	37	0	11	1	5	99	25	6	46	14	3	63	25	0	59	11	2	62	23	1
43	9	2	78	21	2	22	10	1	76	26	1	11	1	2	96	22	4	58	21	4	57	24	0	82	24	0	86	22	3
47	11	2	62	29	2	35	8	0	46	19	2	21	2	2	88	24	3				71	29	2	69	23	1	52	14	1
52	10	4	76	26	1	46	7	0	55	18	0	10	2	3	126	31	6							54	11	2	44	19	2
34	11	0				48	8	3	56	14	2	24	5	1	122	22	5							72	23	1	62	23	0
72	18	3	52	10	2	26	6	2	74	19	2	28	1	2	127	24	2	46	18	2	37	16	2	56	19	1	95	32	1
60	21	0	62	16	7	38	7	2	61	18	2	11	1	2	121	29	2	27	10	4	48	22	3	71	23	1	92	24	1
52	13	0	43	12	5	36	11	1	59	16	1	14	2	5	132	25	2	34	9	2	42	21	2	62	19	0	86	21	2
54	13	2	43	12	11	32	11	2	67	32	1	12	2	5	108	23	0	30	12	0	59	22	2	46	14	1	93	22	0
51	9	4	66	17	2	35	10	4	98	29	1	18	3	4	104	17	0	29	8	2	54	14	0	54	22	0	96	19	2
69	15	2	86	21	6	26	14	1	62	21	2	17	5	3	126	22	3	38	13	0	47	19	1	44	24	2	66	21	0
57	18	1	42	8	7	38	12	2	76	21	0	22	5	4	114	36	0	35	14	3	49	21	1	54	21	2	71	25	1
42	12	3	56	9	0	51	11	1	68	16	2	12	2	6	91	28	4	46	12	1	44	22	3	51	11	0	101	32	0
52	11	2	58	14	1	39	15	2	66	19	2	16	1	4	104	26	3							42	15	2	81	28	2
36	12	1	38	12	3	23	4	1	91	24	0	18	3	3	98	32	2										89	21	4
36	12	2	62	15	2	39	12	5	57	21	1	10	2	3	143	33	2	49	11	3	36	12	1	122	32	1	88	23	2
44	20	3	67	16	2	29	7	3	94	36	0	13	1	3	139	27	1	32	9	3	51	16	0	148	31	6	65	22	3
46	15	2	78	32	1	49	8	4	73	17	2	12	1	16	152	41	2	49	16	3	58	26	0	136	28	3	61	26	0
40	8	3	52	12	1	26	7	0	52	18	3	21	2	3	138	28	1	57	24	0	57	19	0	117	26	0	69	28	1

*Cf. footnote to table 4, p. 326.

42	12	2	65	14	3	46	12	6	75	22	1	17	2	7	106	29	2	34	8	4	46	17	3	92	21	1	59	23	1
45	14	3	58	20	0	22	5	2	52	18	1	21	3	5	136	33	2	51	14	2	82	35	2	136	32	3	65	31	2
42	8	2	54	14	5	49	9	1	58	27	3	9	1	8	123	27	2	41	11	2	39	15	1	108	23	1	44	21	2
44	12	4	42	8	2	61	14	9	64	19	1	31	4	4	96	26	3	42	13	2	51	17	2	128	24	3	67	28	0
41	15	1	73	24	4	29	11	0	89	18	2	16	1	3	93	29	3				49	22	0				76	26	4
52	14	2	61	17	1	39	10	1	62	29	0	19	3	8							63	36	0						
46	14	1	57	14	4	43	12	1	68	15	1	13	3	3	185	45	0	29	8	1	44	13	2	77	18	2	86	26	3
51	16	0	62	16	4	35	11	1	64	17	2	12	3	7	161	36	4	49	12	0	38	14	1	66	18	1	88	21	0
46	10	2	67	23	4	38	8	0	67	13	2	12	0	5	158	42	7	46	11	0	41	16	2	72	16	2	85	27	0
61	16	1	32	7	3	29	8	0	58	16	2	13	2	6	168	36	3	33	6	2	44	11	2	81	23	1	103	24	0
33	7	4	46	16	6	39	10	2	53	13	0	19	4	10	190	44	2	38	14	0	43	15	2	56	13	2	83	20	3
56	17	3	60	17	2	24	10	2	61	16	2	12	1	3	178	39	2	32	8	2	38	15	0	74	25	0	68	22	1
32	9	2	61	17	2	21	9	4	64	16	4	6	0	5	186	38	6	26	8	5	56	24	1	47	12	1	62	19	2
38	16	3	48	21	3	29	6	3	76	16	0	20	1	6	174	40	5	44	11	1	52	20	0				71	21	1
29	12	2	53	16	2	24	8	0	62	13	2	9	2	4	182	42	2	30	9	0	71	19	3				79	18	2
62	15	2	68	25	2	38	7	2	72	18	4	19	1	5	162	31	4	21	6	4									

TABLE 8

*Numbers of microörganisms in the soil on July 18, 1921**

4A		5A		7A		9A		11A		18A		19A		7B		11B		19B	
B+A	A	B+A	A	B+A	A	B+A	A	B+A	A	B+A	A	B+A	A	B+A	A	B+A	A	B+A	A
85*	23	114	31	41	7	132	26	35	1	141	36	38	11	71	24	91	22	76	15
84	21	122	24	27	6	108	24	16	2	106	39	47	18	51	12	123	29	74	21
66	22	99	39	46	11	102	17	24	2	103	33	55	19	74	23	97	23	93	32
86	24	153	48	32	11	143	31	23	1	81	18	36	6	52	14	102	19	66	19
84	30	111	38	28	12	121	36	18	2	148	42	28	7	68	21	114	26	67	24
75	18	118	42	34	13	116	32	26	2	119	32	61	19	96	26	95	28	65	18
76	25	109	24	30	10	105	25	21	1	110	24	47	11	58	14	84	18	76	22
74	23	88	36	28	5	129	17	33	1	139	29	51	13	66	22	118	24	59	14
82	28	133	38	27	7	134	28	17	2	97	34			71	31			77	20
58	16	97	24	41	13	122	32							67	22			63	23
44	19	106	32	38	12	96	24	22	0	117	36	35	14	74	21	79	30	90	21
67	24	89	28	22	8	97	22	27	2	134	43	22	8	78	23	66	22	82	17
79	27	93	25	29	6	99	27	12	0	91	25	43	12	88	23	84	27	72	14
51	18	102	27	24	11	113	23	24	1	99	34	51	14	76	26	98	24	81	27
65	23	86	26	46	9	112	22	27	2	73	12	53	18	60	22	76	24	64	21
41	12	92	14	36	8	107	32	26	1	93	37	35	17	61	24	81	19	91	26
72	22	96	21	44	14	106	24	25	2	77	19	37	14	68	16	58	18	66	25
44	11	82	26	41	7	106	23			82	18	31	16	64	23	104	29	62	18
48	12	84	24	42	14	132	42			97	16			63	17			53	17
43	10	98	26	31	11	98	25			127	31			49	24			67	15
75	23	81	28	31	14	106	28	21	2	131	34	45	7	79	26	88	19	77	21
48	13	142	34	30	9	118	27	41	1	98	26	48	14	69	18	98	22	58	18
79	27	153	32	26	8	131	21	37	0	102	32	58	17	48	17	119	26	98	17
56	15	139	46	24	8	85	22	23	0	118	35	31	12	56	18	107	28	73	26

*Cf. footnote to table 4.

42	14	116	38	32	6	148	46	30	2	107	36	45	12	62	16	102	21	94	21
53	13	92	22	27	6	79	23	33	1	83	23	51	11	57	20	115	29	64	20
44	14	104	30	29	8	117	23	49	1	73	19	41	18	76	23	81	26	59	18
41	11	143	38	33	9	98	22	42	1	129	27	57	13	59	18	92	21	71	20
53	15	117	37	32	8	124	24					54	15	61	19	126	32		
49	13	94	27	37	7	82	18							65	21	118	24		
68	19	110	31	45	11	92	17	38	4	102	18	48	16	69	17	87	26	102	26
76	18	83	32	46	11	102	24	19	2	124	17	49	14	109	27	61	22	71	19
67	21	97	28	48	9	106	19	17	1	105	24	55	15	116	31	79	23	96	26
98	20	92	33	48	16	104	18	31	1	109	31	49	14	89	21	81	27	69	27
61	11	138	41	53	13	83	18	33	3	103	27	39	8	92	23	102	35	84	27
86	16	115	28	39	12	89	16	18	2	121	29	34	7	81	32	73	18	95	29
89	14	131	34	31	9	114	18	26	4	89	21	56	14	112	33	61	18	101	28
56	15	130	39	49	13	84	14	34	5	91	34	68	12	72	22	72	27	78	26
82	21	112	28	52	14	94	13			76	24			63	11				
101	19	122	36	44	9					90	26								
86	22	128	32	31	9	167	28	59	9	112	33	34	8	104	28	69	19	66	17
91	19	98	19	29	5	182	51	24	2	137	32	50	22	110	42	97	16	68	21
102	26	92	18	37	9	143	35	28	1	125	21	56	13	101	33	94	24	45	13
76	16	162	23	34	6	124	28	27	2	138	34	48	14	82	26	82	15	66	17
98	17	79	16	38	6	98	24	37	1	112	32	45	14	68	27	112	28	71	19
69	11	103	16	29	8	155	32	22	1	102	23	47	17	94	29	73	18	69	18
73	12	122	38	19	5	138	25	43	5	91	14	33	11	71	31	92	26	72	19
91	18	118	26	46	12	162	27	38	3	106	28	34	12	72	22	115	32	49	17
76	18	131	36	42	9	170	38	18	1	131	29			67	19	77	20		
72	16	137	34	16	6			33	2	127	35					109	28		

TABLE 10

*Numbers of microörganisms in the soil on September 22, 1921**

4A		5A		7A		9A		11A		18A		19A		7B		11B		19B	
B+A	A	B+A	A	B+A	A	B+A	A	B+A	A	B+A	A	B+A	A	B+A	A	B+A	A	B+A	A
77*	28	154	32	44	14	134	36	47	4	145	32	58	14	131	25	98	31	170	59
101	26	156	38	36	15	152	54	57	7	148	48	46	9	108	26	121	39	183	52
102	28	124	30	39	12	114	57	55	6	170	61	54	11	117	29	124	41	142	54
93	32	167	51	36	8	100	42	44	5	146	44	42	7	105	31	114	43	170	56
78	24	164	57	57	23	98	26	51	7	158	42	55	13	111	23	148	42	169	66
111	22	108	27	29	9	122	49	43	13	153	46	49	12	106	34	137	36	173	53
69	18	149	43	54	19	108	28	39	4	157	71	48	12	113	31	129	34	137	49
83	27	138	40	69	19	113	37	42	8	163	53	62	11	101	29	133	32	142	44
102	20	214	70	51	14	126	38	44	3	166	52	74	16	104	32	109	31	113	25
82	18	203	44	39	7	104	40	37	1	238	59	66	12	99	29	73	23	98	29
59	13	184	36	67	16	114	44	28	3	169	45	62	13	86	27	132	44	158	37
110	24	182	37	46	12	106	32	55	4	246	72	97	21	89	26	128	39	112	31
100	20	224	56	41	15	132	42	52	5	253	82	81	10	101	34	113	43	176	45
52	12	193	74	66	20	110	42	61	4	186	46	53	12	92	29	79	24	124	37
102	26	178	62	43	12	112	39	32	2	234	71	59	14	123	36	117	29	114	28
55	11	197	56	56	13	103	35	42	6	207	58	63	13	78	37	122	34	106	29
65	16	222	53	57	14	139	28	59	4	136	37	52	10	98	39	103	28	153	34
58	17	186	38	64	17	174	47	54	8	147	38	59	14	79	26	98	26	141	39
69	19	227	49	53	12	193	34	74	8	144	42	62	18	92	51	89	33	146	36
71	23	178	41	57	18	172	52	32	2	138	44	108	22	92	29	81	24	162	45
49	10	230	52	33	11	146	32	29	2	190	56	55	16	102	47	123	37	132	37
37	12	256	68	28	15	118	32	44	5	152	42	69	13	89	33	71	23	149	42
79	19	218	67	46	12	114	41	37	3	212	68	77	14	103	42	88	33	127	43
60	14	168	34	39	7	153	46	49	4	141	46	83	16	104	43	112	31	144	42

*Cf. footnote to table 4, p. 326.

106	28	136	37	33	6	136	38	63	9	145	36	66	13	101	26	130	38	142	41
70	19	178	46	44	13	92	22	66	14	192	48	72	16	112	27	123	41	149	43
66	15	169	49	66	13	102	26	77	24	138	41	63	14	139	31	126	36	106	29
59	15	168	42	49	17	130	38	41	8	147	43	91	19	99	24	128	37	144	34
78	23	197	45	46	18	98	26	55	12	134	40	58	13	109	31	111	29	89	28
73	22	194	46	49	13	74	18	86	10	204	49	73	14	112	31	121	41	137	36
76	26	192	48	68	19	111	27	44	8	223	58	69	12	82	29	92	26	112	31
91	21	184	42	65	23	83	25	49	7	118	37	64	14	77	26	99	28	124	29
84	31	124	30	38	9	129	36	61	7	116	24	68	21	104	19	98	28	137	34
61	20	152	38	43	16	106	33	48	4	159	34	64	11	108	26	88	19	99	29
102	23	130	46	47	12	97	18	49	9	133	30	56	14	103	24	124	26	151	42
89	22	104	28	48	14	110	45	38	6	146	37	63	19	92	29	92	28	133	29
83	23	164	49	34	12	168	43	51	6	152	43	49	14	99	28	66	21	112	28
63	18	128	31	42	7	132	52	79	16	138	29	67	18	139	31	95	28	81	33
68	16	126	32	39	6	153	57	41	6	155	39	78	17	109	28	113	35	123	28
72	19	143	39	41	8	129	41	62	6	182	48	83	18	88	26	137	39	92	31

TABLE 9

Summary of results reported in table 8

PLOT NUMBER	MEAN		σ		C.V.		Em	
	B+A	A	B+A	A	B+A	A	B+A	A
	colonies	*colonies*			*per cent*	*per cent*	*per cent*	*per cent*
4A	69.6 ± 1.67	18.3 ± 0.49	17.56 ± 1.18	5.14 ± 0.35	25.2 ± 1.7	28.1 ± 1.9	2.4	2.7
5A	111.1 ± 2.02	30.3 ± 0.74	21.25 ± 1.43	7.74 ± 0.52	19.1 ± 1.3	25.5 ± 1.7	1.8	2.4
7A	35.3 ± 0.84	9.4 ± 0.27	8.83 ± 0.59	2.86 ± 0.19	25.0 ± 1.7	30.4 ± 2.0	2.4	2.9
9A	116.1 ± 2.4	25.7 ± 0.86	24.73 ± 1.7	7.85 ± 0.54	21.3 ± 1.5	30.5 ± 2.1	2.07	3.3
11A	28.5 ± 1.0	2.0 ± 0.17	9.7 ± 0.7	1.63 ± 0.12	34.0 ± 2.4	81.5 ± 6.0	3.5	8.5
18A	105.5 ± 1.97	27.5 ± 0.74	20.0 ± 1.38	7.57 ± 0.49	18.9 ± 1.3	27.5 ± 1.8	1.9	2.7
19A	45.0 ± 1.06	13.3 ± 0.39	10.05 ± 0.76	3.74 ± 0.28	22.3 ± 1.7	28.1 ± 2.1	2.35	2.9
7B	74.1 ± 1.7	22.9 ± 0.58	17.53 ± 1.2	6.08 ± 0.42	23.7 ± 1.6	26.5 ± 1.8	2.3	2.5
11B	92.1 ± 1.81	23.5 ± 0.48	17.76 ± 1.27	4.71 ± 0.33	19.3 ± 1.4	20.0 ± 1.4	1.96	2.04
19B	73.6 ± 1.4	20.4 ± 0.47	13.81 ± 0.99	4.58 ± 0.33	18.8 ± 1.3	22.4 ± 1.6	1.9	2.3

TABLE 11

Summary of results reported in table 10

PLOT NUMBER	MEAN		σ		C.V.		Em	
	B+A	A	B+A	A	B+A	A	B+A	A
	colonies	*colonies*			*per cent*	*per cent*	*per cent*	*per cent*
4A	75.7 ± 1.99	20.5 ± 0.58	18.7 ± 1.4	5.5 ± 0.61	24.7 ± 1.8	26.8 ± 2.0	2.63	2.83
5A	172.7 ± 3.8	45.1 ± 1.26	35.6 ± 2.7	11.9 ± 0.9	20.6 ± 1.6	26.4 ± 2.0	2.2	2.8
7A	47.6 ± 1.22	13.5 ± 0.47	11.46 ± 0.87	4.42 ± 0.33	24.1 ± 1.8	32.7 ± 2.4	2.56	3.48
9A	122.7 ± 2.77	37.5 ± 1.06	25.98 ± 1.96	10.0 ± 0.75	21.2 ± 1.6	26.7 ± 2.0	2.26	2.83
11A	50.4 ± 1.44	6.8 ± 0.32	13.54 ± 1.02	4.35 ± 0.33	26.9 ± 2.0	64.0 ± 4.6	2.86	4.7
18A	167.0 ± 3.77	47.3 ± 1.37	35.36 ± 2.68	12.9 ± 0.98	21.2 ± 1.6	27.3 ± 2.1	2.26	2.9
19A	65.5 ± 1.5	13.8 ± 0.36	14.0 ± 1.06	3.41 ± 0.26	21.4 ± 1.6	24.7 ± 1.9	2.3	2.6
7B	102.4 ± 1.55	30.6 ± 0.69	14.5 ± 1.1	6.5 ± 0.49	14.2 ± 1.1	21.7 ± 1.6	1.54	2.25
11B	109.6 ± 2.17	32.5 ± 0.69	20.44 ± 1.55	6.54 ± 0.48	18.7 ± 1.4	20.1 ± 1.5	2.0	2.1
19B	134.3 ± 2.75	38.4 ± 1.06	25.77 ± 2.01	9.95 ± 0.75	19.1 ± 1.5	25.9 ± 1.9	2.05	2.76

TABLE 12

Numbers of fungi in the soil on July 18 and September 22, 1921, as determined on special acid media

PLOT NUMBER	NUMBER OF FUNGI PER GRAM	
	July 18	Sept. 22
4A	31,000	45,600
5A	54,000	91,000
7A	56,000	63,000
9A	47,000	45,900
11A	115,000	107,900
18A	73,000	87,600
19A	61,000	48,200
7B	28,000	16,900
11B	44,000	34,200
19B	32,000	26,200

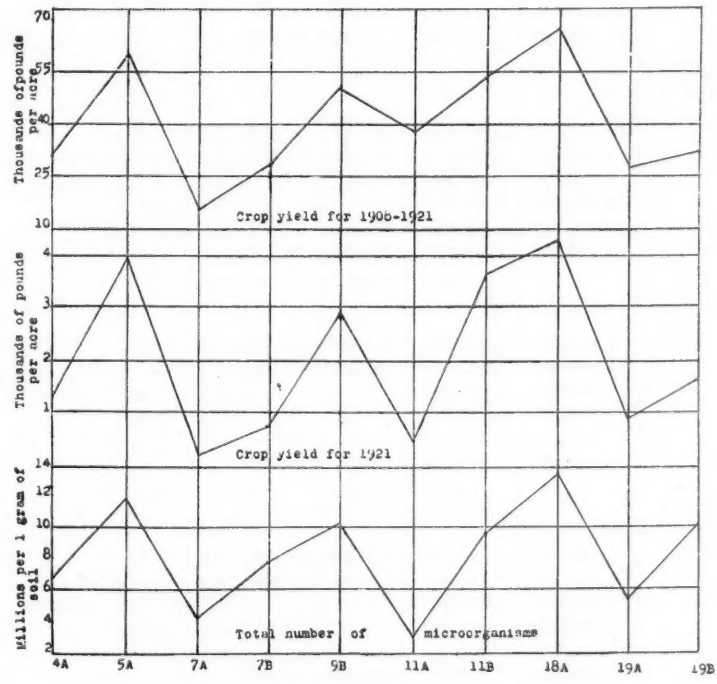

FIG. 2. CROP YIELDS FROM PLOTS AND BACTERIAL NUMBERS

Figures for yields designate thousands of pounds of dry matter per acre; the numbers of microörganisms are in millions per gram of moist soil.

TABLE 13

Summary of results—Average of 4 samplings

PLOT NUMBER	B + A	A	F*	F†	AVERAGE MOISTURE	AVERAGE REACTION	SOIL TREATMENT
	number	*number*	*number*	*number*	*per cent*	*pH*	
4A	7,490,000	920,000	264,000	31,000	15.0	5.8	Minerals only
	4,700,000	1,290,000	203,000	45,600	5.3	5.4	
	6,960,000	1,830,000			12.3	5.5	
	7,570,000	2,050,000			13.8	5.7	
Aver.	6,680,000	1,520,000	234,000	38,300			
Aver. / *B + A*		*22.7%*	*3.5%*				
5A	12,450,000	2,320,000	365,000	54,000	10.0	5.6	Manure
	6,060,000	1,810,000	303,000	91,000	4.8	5.0	
	11,110,000	3,030,000			12.5	5.4	
	17,270,000	4,510,000			11.7	5.5	
Aver.	11,720,000	2,920,000	334,000	72,500			
Aver. / *B + A*		*24.5%*	*2.9%*				
7A	4,680,000	1,360,000	240,000	56,000	12.0	4.0	Control, no fertilizer
	3,610,000	940,000	200,000	63,500	5.3	4.0	
	3,530,000	940,000			8.2	5.1	
	4,760,000	1,350,000			10.7	5.1	
Aver.	4,150,000	1,150,000	220,000	59,750			
Aver. / *B + A*		*27.7%*	*5.3%*				
9A	9,990,000	1,780,000	170,000	47,000	10.0	5.8	$NaNO_3$ + minerals
	6,650,000	2,030,000	163,000	45,900	3.7	5.3	
	11,610,000	2,570,000			12.6	5.4	
	12,270,000	3,750,000			12.5	5.6	
Aver.	10,130,000	2,530,000	167,000	46,450			
Aver. / *B + A*		*25.0%*	*1.65%*				
11A	2,780,000	380,000	457,000	115,000	12.0	3.9	$(NH_4)_2SO_4$ + minerals
	1,560,000	230,000	433,000	107,900	4.8	3.9	
	2,850,000	200,000			11.4	3.9	
	5,040,000	680,000			12.6	4.7	
Aver.	3,060,000	370,000	445,000	111,450			
Aver. / *B + A*		*12.1%*	*14.5%*				

* Results based on tables 4 and 6.

† Results based on table 12.

TABLE 13—*Continued*

PLOT NUMBER	B + A	A	F	F	AVERAGE MOISTURE	AVERAGE REACTION	SOIL TREATMENT
	number	*number*	*number*	*number*	*per cent*	*pH*	
18A	14,930,000	3,380,000	235,000	73,000	10.0	5.8	Manure + $NaNO_3$ + minerals
	12,800,000	2,970,000	300,000	87,600	5.0	5.2	
	10,550,000	2,750,000			12.1	5.3	
	16,700,000	4,730,000			11.4	5.6	
Aver.	13,750,000	3,460,000	268,000	80,300			
Aver. / *B + A*		*25.2%*	*1.95%*				
19A	6,310,000	1,460,000	243,000	61,000	10.0	5.4	Minerals only
	4,010,000	1,190,000	206,000		3.6	5.0	
	4,500,000	1,330,000			9.8	5.0	
	6,550,000	1,380,000			11.2	5.4	
Aver.	5,340,000	1,340,000	225,000	61,000			
Aver. / *B + A*		*25.1%*	*4.2%*				
5B‡	22,000,000			29,400	12.0	7.0	Manure + minerals + lime
7B	7,720,000	2,260,000	146,000	28,000	10.0	6.4	Lime only
	5,090,000	2,030,000	114,000	16,900	3.1	6.2	
	7,410,000	2,290,000			9.8	6.8	
	10,240,000	3,060,000			11.4	6.2	
Aver.	7,620,000	2,410,000	130,000	22,450			
Aver. / *B + A*		*31.6%*	*1.7%*				
11B	10,140,000	2,410,000	180,000	44,000	10.0	6.0	$(NH_4)_2SO_4$ + minerals + lime
	7,710,000	2,000,000	130,000	34,200	3.1	5.8	
	9,210,000	2,350,000			9.9	6.0	
	10,960,000	3,250,000			9.0	5.5	
Aver.	9,510,000	2,520,000	155,000	39,100			
Aver. / *B + A*		*26.5%*	*1.63%*				
19B	12,400,000	3,100,000	164,000	26,200	10.0	6.6	Minerals + lime
	7,300,000	2,300,000	163,000		3.4	6.8	
	7,360,000	2,040,000			9.8	7.0	
	13,430,000	3,840,000			10.1	6.5	
Aver.	10,120,000	2,820,000	164,000	26,200			
Aver. / *B + A*		*27.8%*	*1.6%*				

‡ This plot had the same treatment as 5A with the addition of lime; it had been sampled but once (Sept. 22), and the results are given here for comparison.

column represents the colonies obtained from one particular plot, at one particular date, with 100,000 dilution or 1000 dilution for special acid medium (table 12). Each group in the column represents the plates counted for each of the different composite samples taken from each plot. The results are calculated by the use of the formulae given in Paper I of this series (16), namely:

$$\text{Average deviation, } \sigma = \sqrt{\frac{\Sigma (Zn - a)^2}{n - 1}}$$

$$\text{Most probable error} = \pm 0.6745 \sqrt{\frac{\Sigma (Zn - a)^2}{n(n - 1)}}$$

$$\text{C.V.} = \frac{\text{the average deviation} \times 100}{\text{mean}}$$

$$\text{Em} = \frac{\text{most probable error} \times 100}{\text{mean}}$$

DISCUSSION OF RESULTS

To be able to discuss the results more thoroughly, all the tables have been condensed into table 13 and figure 2 which show at a glance the influence of fertilization upon the numbers of the different groups of microörganisms in the soil, as determined by the plate method.

The lowest number of microörganisms is found in the plot receiving annually ammonium sulfate without any application of lime. This plot has become so acid that there was practically no crop during the summer in question; there was, however, a second crop consisting chiefly of crab grass. This ammonium sulfate plot gave the lowest number of microörganisms, since the reaction of the soil during the major part of the summer was less than pH 4.0, which is a reaction distinctly unfavorable to bacterial activities. The actinomycetes were even more affected than the bacteria, so that not only did the total number of microörganisms (except the fungi) drop down to 3 million per gram, but the percentage of the actinomycetes was only 12.1, while in the untreated plot it was 27.7. This is due to the fact that the actinomycetes, as shown by the writer elsewhere (18), are very sensitive to acid conditions. However the acid reaction did not prevent the growth of the fungi, which developed even to a greater extent due to the presence of a good source of nitrogen and probably due to the lack of competition from the bacteria and actinomycetes. There were 111, 450 fungi per gram of soil, in this plot, using the acid medium, a greater number than that of any other plot. This was equal to 14.5 per cent of the number of bacteria and actinomycetes on the bacterial plate. In this plot we find a striking correlation between a low crop yield (practically a minimum) and a low number of microörganisms. The low number of actinomycetes and high number of fungi are rather a result of the reaction of the plot than of any lack in fertility. In the study of this plot, the correlation found is between bacterial activities, as expressed in numbers of microörganisms, and the chemial condition in the soil, rather than its fertility.

As soon as lime is added to the soil and the acidity resulting from the use of ammonium sulfate is neutralized, there is a rise both in crop productivity and bacterial numbers. This reverse picture is found in plot 11B which received, in addition to an equivalent amount of ammonium sulfate and minerals as 11A, also limestone at the rate of 2 tons per acre every 5 years. The productivity of this plot is very high, giving throughout the whole period as good yields as the sodium nitrate plot (9A), but smaller yields than the two manured plots (5A and 18A). The number of microörganisms on this plot are only a trifle less than those on the nitrate plot and appreciably less than in the two manured plots. The percentage of actinomycetes increased from 12.1 to 26.5, or from the lowest of the whole series to the general average, while the fungi dropped from 111,450 to 39,100 per gram on the acid media and from 14.5 to 1.63 per cent on the general plates. This bears out again the statement made in the previous paragraph that the total and relative numbers of actinomycetes and fungi are a function of the soil reaction rather than of the chemical and bacteriological condition of the soil. The correlation between the productivity of the soil and total number of microörganisms is again brought out.

Plot 9A which received annually sodium nitrate behaved in general like 11B, as seen from the following correlation:

	PLOT 9A	PLOT 11B
Total bacteria	10,113,000	9,500,000
Actinomycetes, per cent	25	26.5
Fungi (acid medium)	46,450	39,100
Fungus ratio on general plate	1.65	1.63
Reaction, pH	5.5	5.8
Total crop yield, lbs.	50,488	53,826

When the fact is kept in mind that the crop yields are quite similar on the two plots (slight differences may be due to preference of plants in question for the particular source of nitrogen or for calcium as a fertilizer), we may conclude that the two fertilizers affect alike the numbers of microörganisms in the soil, as long as there is enough lime in the soil to neutralize the acids left or formed from the ammonium sulfate. Again the bacterial numbers in the soil are found to be a function of the productivity of the soil, when properly determined and when the variability is accounted for.

When the two plots 9A and 11B are compared with plots 4A and 19A which received the same amount of minerals but no nitrogenous fertilizer, we find that the addition of the nitrogenous fertilizer, where it did not result in an acid reaction, as in 11A, resulted in an increase both of crop production and numbers of microörganisms. It is interesting to note that, while the yield from 9A is nearly double the yield obtained by averaging 4A and 19A, the numbers of microörganisms are also nearly double. While the ratio of actinomycetes remained the same, the ratio of the fungi to the total number of microörganisms

is 3.7 per cent for the plots without any nitrogenous fertilizer and 1.64 per cent for the two fertilized plots (9A and 11B). This may be due either to a slight difference in reaction, which is somewhat more acid in the former, or to a stimulating effect of the nitrogenous fertilizers upon the activities of bacteria and actinomycetes to a much greater extent than of the fungi.

If lime is added to the soil in addition to minerals (plot 19B) there is a decided increase in the number of microörganisms. The reaction of all the plots not receiving lime is decidedly acid and we may assume that the activities of microorganisms in these plots are kept somewhat in check. The soil in 11B receiving lime is still decidedly acid due to the large amounts of ammonium sulfate used. In 19B, however, the addition of lime resulted in making the soil neutral. This resulted in an increase in the ratio of actinomycetes, a decided decrease both in the numbers and ratio of fungi and an increase in the total numbers of microorganisms (bacteria + actinomycetes). This is accompanied by an increase in crop yield so that the crop obtained from 19B is almost double, for 1921 than that of 19A. If there is no close parallel as in the case of the previous plots, it is no doubt due to the lack of uniformity of the soil in the different plots as seen from 4A and 19A which, although receiving the same treatment, gave different crop yields during the different periods.

Taking up the two manured plots, one without (5A) and one (18A) with sodium nitrate, we obtain the greatest number of microörganisms. The fact that manure greatly stimulates an increase in bacterial numbers has been brought out by various investigators, Engberding (2), Temple (15), and others. The numbers of actinomycetes increased with the bacteria so that the same ratio is obtained. As to the fungi, there is a definite increase in numbers in both plots as shown by the use of the special acid medium, but the ratio of fungi to the total number was decreased somewhat, more so in the plot that received also sodium nitrate. This would indicate that the addition of manure to the soil results in an increase in the numbers of fungi, but not to such an extent as do the bacteria and actinomycetes, which results in a drop in the ratio of fungi. In the case of these two manured plots, we find again a definite correlation between the soil productivity, as indicated by the crop yield for the whole period, and numbers of microörganisms. The plot (5B) that received both manure and lime was sampled only once (Sept. 22). It indicated a further increase in the total number of microörganisms (22,000,000 as compared with 17,270,000 in 5A at the period of sampling) and a drop in the fungus numbers which would be expected from the change of reaction to neutrality. This was also accompanied by a greater crop yield.

The two plots receiving no mineral or nitrogenous fertilizers at all are 7A and 7B, the latter being the limed plot. The first plot has become so exhausted due to continuous cropping without fertilizer that the crop of hay the year under study, was almost negligible. This may be due either to the high acidity of the plot, particularly in the early part of the summer, to the exhaustion of nutrients or accumulation of toxic products. Whatever that may be,

the crop yield was paralleled by the number of microörganisms. With the exception of 11A, 7A gave the lowest numbers of microörganisms, including both bacteria and actinomycetes. The ratio of the latter was not so low as in 11A, but remained normal, while the number and ratio of the fungi was much above normal (in comparison with plots 4A or 19A), although less than in 11A. This would indicate that the conditions that brought about the lack of fertility in plot 7A, due to continued cultivation, injured bacteria and actinomycetes alike, but not the fungi. If it is a question of reaction, which may be quite probable, it is easily explained by the fact that the acid reaction favors the development of fungi in preference to the bacteria and actinomycetes. However, the latter organisms are not injured to such an extent as in Plot 11A, possibly due to the fact that the organic acids formed in 7A and which account chiefly for the acidity of this plot are less injurious to actinomycetes than the inorganic acids resulting from the application of ammonium sulfate in 11A. As a matter of fact, the actinomycetes can use organic acids as sources of carbon and break them down thus tending to make the medium less acid.

The addition of lime to the plot receiving no fertilizer (7B) resulted in an increase in the numbers of microörganisms, an increase in the ratio of actinomycetes, a decrease in the ratio and numbers of fungi, and an increase in crop production.

It would therefore seem conclusive, from the above considerations, that the total number of microörganisms as determined by the plate method can serve as a function of the bacteriological condition of the soil and as an index of soil fertility. The relative numbers of bacteria, actinomycetes and fungi indicate also the chemical condition of the soil.

Manure has the greatest effect in stimulating the numbers of microörganisms in the soil. Next to the action of manure, liming of acid soils stimulates the development of bacteria and actinomycetes. While manure offers a source of energy for the activities of bacteria, fungi and actinomycetes, lime neutralizes the soil acidity making the soil a more favorable medium for the development of bacteria and even more so for actinomycetes, while the fungi are depressed either due to the unfavorable effect of the reaction or to the competition of the other microörganisms (antagonistic effects included). The addition of lime stimulating the development of bacteria and actinomycetes, which are able to decompose the soil organic matter, thus making the nitrogen stored away available for higher plants, is equivalent to nitrogen fertilization. The addition of lime to the soil is found to have a more stimulating effect upon the number of microörganisms than upon crop yield, as shown in Fig. 2 (7B and 19B). This is due to two or more factors. The addition of lime in the above cases brought about a change in reaction critical to the growth of various bacteria, like Azotobacter, and actinomycetes; the plants which may not be so sensitive to the acid reaction of the soil as certain groups of bacteria are probably not affected as favorably as those bacteria. The addition of lime to an acid soil also brings about a redistribution of the various groups of soil

microörganisms (qualitative) which may account for the lack of perfect parallelism.

Artificial fertilizers serve as direct plant food for higher plants and stimulate the activities of microörganisms, so far as those developing on the plate are concerned, only to a smaller extent. They modify largely the activities of microörganisms in the soil due to the secondary reaction produced, such as change in reaction or physical condition of soil, etc., which will allow specific groups of microörganisms to develop.

When the different periods of sampling are compared, we find that, at the end of dry spells, as in the case of the second sampling, the numbers of microorganisms drop down. The question then arises, when is the proper time to sample the soil, so as to obtain a representative bacterial flora? If the soil is sampled after a long dry period, the numbers will be much below the average, the drop not taking place alike in all soils. As a simple example, we may cite the fact that although in 5A, the numbers dropped from the May to the June sampling more than one-half, then increased to nearly three times in September, in plot 7A they dropped only one-quarter and then increased again by one-third. This is due to two causes: the conditions in 7A are unfavorable for bacterial activities and the forms present are more or less resistant, such as spore formers, etc., while 5A offers good condition for bacterial development. A prolonged dry period therefore, is bound to have a much greater effect on the bacteria in 5A than in 7A. Then again when the soil becomes again moist, the abundant organic matter in 5A will allow a rapid development of the bacteria, while in 7A it will take place only to a limited extent.

This brings us to the second point: should the soils be sampled shortly after a heavy rainfall? In this case the reverse conditions will hold true with results more favorable for the optimum soil conditions, as pointed out previously. The prolonged drying followed by heavy rainfall will act as a rapid shift in bacteriological equilibrium (see table 1), which will not be manifested alike in poor and fertile soils. The most ideal time for sampling would be not after a dry period and not soon after a wet period, but somewhere in between. However, before we have more definite information on the change of bacterial equilibrium in the soil, we have to take several samples during the growing season and base our results upon these.

SUMMARY

The results obtained from the investigations presented in this and the previous two papers dealing with the numbers of microörganisms in the soil can be summarized as follows:

1. The results based on one soil sample only are valueless. Several samples of the same soil, composite, if possible, should be used.

2. A large enough number of plates should be used (8–10 for each soil sample) so that the most probable error of the mean for the total number of micro-

organisms in each soil be less than 5 per cent. When it is reduced to 2 or 2.5 per cent the results are more valuable.

3. Only the numbers of bacteria and actinomycetes should be determined on the regular plate. Special acid media should be used (pH = 4.0), with a dilution one-hundredth of that used for the determination of the total number of microörganisms, for the determination of numbers of fungi in the soil.

4. Synthetic media should be used. The plates should be incubated at 25–28°C. for 7 days, or at room temperature for 14 days. All colonies should be counted on the plate, with an optimum of 50—200 colonies of microörganisms per plate. The only plates discarded from the count are those badly overgrown with fungi.

5. With these precautions carefully observed, it has been found that fertilizer treatment exerted the following influences upon the numbers of microorganisms in the soil, using a sandy loam, not very rich in organic matter:

(*a*) Potassium salt and phosphates stimulated the development of microorganisms, more so in the presence of lime than in its absence.

(*b*) The addition of lime resulted in a decrease in the numbers of fungi and an increase in numbers of bacteria and actinomycetes.

(*c*) Sodium nitrate stimulated the development of bacteria and actinomycetes but not of fungi. Ammonium sulfate, making the soil distinctly acid, stimulated the development of fungi, with a decided decrease in the numbers of bacteria and particularly actinomycetes. Where lime was used together with the ammonium sulfate, the stimulating influence was equal to that of sodium nitrate.

(*d*) Manure exerted a decided stimulating effect upon all groups of microorganisms developing on the plate.

6. Crop production ran nearly parallel, in the particular soil, with the numbers of microörganisms in the soil developing on the plate.

CONCLUSION

The numbers of microörganisms in the soil, when determinations are carried out under proper conditions, with due allowance for the variability of the methods used and soils, can serve as one function for measuring the bacteriological condition of the soil and crop production. To determine the bacteriological condition properly, we must find other functions, which will be the subject of the following investigations.

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SILICA AND SILICATES IN RELATION TO PLANT GROWTH AND COMPOSITION

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INTRODUCTORY

The functions of silica in plant economy are but little understood. Most writers on plant physiology class silicon with the non-essential elements, but with the reservation that although it may be dispensed with, many plants do better when it is present, if for no other reason than that they are accustomed to it. Deposits of silica are supposed to serve a useful purpose by hardening the outer walls of the plant stems, sharpening the edges of leaf blades or stiffening hairs, all of which are protective agents.

It has been thought that silica serves to stiffen the stems of cereals, and that fertilization with soluble silicates would thus be useful in preventing lodging of the crop, but according to Sachs (13, p. 289) the theory has no basis in fact. Pfeffer (12, vol. 1, p. 414) suggests that silicon may function like calcium in helping further to reduce the amount of potassium or phosphorus necessary for development. Certain plots at Rothamsted are dressed with sodium silicate and on the phosphate-starved plots the silicate appears to have caused marked increases in the barley crop. Hall and Morison (7) have made a study of these plots and conclude that the silicate causes an increased assimilation of phosphorus, the seat of action being in the plant and not in the soil. That is, the influence of the silicate upon the plant has enabled it to secure an increased amount of phosphorus from the soil, although from the lack of phosphorus fertilization the soil had become highly deficient in that element. A connection between the presence of silica and utilization of phosphorus had been noted by Kreuzhage and Wolff (9) from the results of solution-culture experiments with oats. In their work, the silica had been dissolved in the minimum amount of potassium hydroxide and added to the solution acid with sufficient nitric acid to neutralize the alkali and retain the silica in colloidal solution. Jennings (8) grew wheat seedlings in various colloidal jellies, and found that 1-per cent silica jelly was of great benefit to growth, while an agar jelly was less beneficial and under some circumstances was distinctly harmful. He concludes that silica is beneficial because absorbed and actually used by the plant.

Cowles (4) and Scheidt (14) have published data showing beneficial results to various crops from applications of dicalcium silicate, a by-product from the manufacture of sodium aluminate. This material contains a readily decomposible calcium silicate, also a certain amount of water-soluble sodium silicate. They attribute its value to both the calcium and silica contained. Conner (3) reports that dicalcium silicate gave better results in field and pot experiments than were obtained from the use of lime. This is attributed to the superior effect of the active silicate in reducing the amount of aluminum in the soil solution, which Connor considers to be the most harmful factor in acid soils. At equivalent hydrogen-ion concen-

tration, aluminum is less soluble as silicate than as hydrate, according to data reported in the article cited.

It has been shown in this laboratory that the bases of dicalcium silicate are quite as effective in reducing lime requirement of soil as are those of ground limestone under similar conditions. Ground blast furnace slag was included in this test, and while its activity was less than that of the other materials mentioned, it was quite appreciable (15). While the bases of slag have thus been shown to be less available, or less active in satisfying the soil's absorptive capacity for bases, it does not necessarily follow that the effect of slag upon plant growth will be inferior to that of limestone. It may possibly have virtues peculiar to itself, and only to be revealed by practical trial. Pot tests have indicated that both finely ground blast furnace slag and precipitated calcium silicate are superior to precipitated calcium carbonate used at the same rate, 4400 pounds per acre, when tested with red clover as the crop (1). And further, the value of several natural silicates as soil amendments in pot experiments has been demonstrated by MacIntire and Willis (10).

OBJECTS OF EXPERIMENT

Consideration of this earlier work led to the belief that instructive results might be obtained from pot experiments in which several carriers of silica and both soluble and insoluble phosphates were applied to various pots, and crops grown under conditions approaching normal. The amounts of silica taken up by plants from that offered in various forms, the effect of applications of calcium carbonate upon the assimilation of silica and the effect of silica upon the amounts of phosphorus utilized by plants from that applied to the soil as soluble monocalcium phosphate and as rock phosphate (floats) were other points considered in planning the experiment.

In particular, it was desired to determine whether the demonstrated value of blast furnace slag is due partly to its silica content, or whether the bases supplied are the sole cause of its beneficial effects. The great quantities of blast furnace slag available in many localities having soils in need of liming, and the apparent effectiveness of the material as a substitute for ground limestone as a soil amendment, led to its inclusion in the present investigation. Furthermore, the possibility suggested itself that blast furnace slag might be both a sufficient source of bases for acid soils and of silica for plants, and that the silica thus supplied might be of positive benefit to crops, especially with respect to increasing the possible utilization of insoluble phosphate, as the work previously cited has suggested. There seems to be still another reason why the use of slag instead of limestone with rock phosphate might be advantageous. Both theory and results of practical field experiments indicate that rock phosphate is most effective when used on a soil not too abundantly supplied with bases. Yet the maintenance of fertility is not possible without legumes, which require lime in some form. A material like slag, less active than the common forms of lime when finely divided and thoroughly distributed in the soil, might be able to supply sufficient calcium and sweeten the soil to an extent sufficient for a satisfactory growth of legumes without making soil conditions too unfavorable for the utilization of rock phosphate.

SOIL, MATERIALS AND PROCEDURE

The soil used for the experiment was Wooster silt loam obtained from the edge of one of the fertility fields on the Station farm; it is not known ever to have been limed, contains but a trace of carbonate and is acid to litmus paper and the Truog test. The soil to the depth of 6 to 7 inches and the subsoil down to 1 foot were taken up separately and after thorough mixing by shoveling were packed in their proper order in 20-inch sewer pipes sunk in the ground for pots. The subsoil was tamped in very firmly to make good contact with the native subsoil at the bottom. The top of the subsoil was within 7 inches from the top of pot. The pots were completely filled with thoroughly compacted soil and finally finished with a slightly convex surface. The object was to secure a very compact subsoil, as exists in the field, and to prevent abnormal conditions as a result of the soil shrinking away from the walls of the pot after a time. Calcium carbonate, silicate, hydrated silica, blast furnace slag and rock phosphate (floats) were applied by removing the upper 6 inches of soil, mixing the materials with it and replacing it in the same manner as it was first put in the pots. Sodium silicate (water glass) and dialyzed silica were diluted with water, sprinkled over the soil removed as stated and the whole mixed. After allowing the mixture to dry, lumps were crushed and the soil was again mixed and replaced in the pot. Potassium and nitrogen were added to all pots in solution containing 70 cc. of 10-per cent potassium nitrate and soluble phosphorus by 73 cc. of 10-per cent monocalcium phosphate where indicated. One or both portions of the solution were diluted to 250 cc. and distributed over the surface of the pots as evenly as possible by means of a separatory funnel. After drying, the soil was thoroughly mixed and put into optimum condition for seeding. Pots receiving soluble phosphate had the equivalent of 2600 pounds per acre of fertilizer containing 2 per cent ammonia, 7 per cent phosphoric acid and 5½ per cent potash. All received nitrogen and potash at the same rate. Rock phosphate was applied at the rate of 1100 pounds per acre; the commercial ground rock was used.

The calcium carbonate used was Baker's Analyzed; each pot limed received 182 gm. which is equivalent to 4 tons per acre. The calcium silicate, corresponding to the formula $CaSiO_3$, was prepared by the interaction of solutions of calcium chloride and sodium silicate. This and blast furnace slag were used at the rate of 100 gm. per pot. The hydrated silica was produced by adding excess of sulfuric acid to diluted water glass, evaporating and washing; pots receiving this also had 200 cc. dialyzed silica, made by adding diluted water glass to excess hydrochloric acid, and dialyzing in collodion bags until nearly free from chlorine. It was still liquid when applied but could be caused to set to a jelly. The blast furnace slag was ground to pass a 100-mesh sieve, and was from the same lot as that employed in other tests previously reported (1, 15). All treatments with silicon compounds were intended to furnish approximately 1000 pounds per acre silicon, and the quantities applied were dependent upon the composition of the material.

Crops on these pots were treated so far as possible the same as those in the field with respect to time of seeding and were found to ripen at practically the same time.

FACTORS AFFECTING YIELDS

The variously treated pots were 30 in number, and were situated in a wire cage with similar pots used for other experiments. The materials applied to individual pots are indicated in table 1, together with yields and composition of crops from pots so treated, and need not be enumerated here. There were sixteen variations in treatment, all but two of which were in duplicate pots. The slag-treated pots were all in one row with duplicates adjacent, but duplicates of other treatments were in separate rows, about 2 rods apart, with the order of treatments reversed. The object of this separation was to determine differences due to local factors, and to prevent any erroneous conclusions. Results obtained indicate that this is a point of some importance, as row 33 was remarkably superior in appearance and yield to the duplicate pots of row 15 in the case of the soybeans grown in 1920. Even in the cases of the adjacent duplicates in row 13, differences in yield and composition are considerable, although there is no consistency which would indicate that such differences were due to more than temporary influences. It is very difficult, if not indeed impossible, to avoid great variability in work of this nature. Even in solution cultures, with every precaution possible, it has been shown (5) that individual plants may vary in dry weight by 50 per cent and duplicate cultures of six plants each by 20 per cent from the mean of 33. While the influence of this factor of variability in individual plants should be less in the case of these pots, which had an average of 30 soybean plants in 1918 and about 25 in 1920, it must still exert an appreciable influence, although probably insignificant in comparison with that of unavoidable differences in preparation and subsequent treatment of pots. The pots were seeded quite thickly, with the idea of thinning, the plants later to secure a uniform stand; after thinning, however, a few plants were accidentally lost. This factor, however, does not appear to have had much influence on the total yield of a pot, as the largest difference between the pots of a pair in 1918 was five plants, a pot with 25 plants yielding 83 gm. crop, while its duplicate with 30 plants yielded but 66 gm. Another pot receiving nearly the same treatment and bearing 31 plants yielded 123 gm. Even those pots with the smallest number of plants had a heavier stand than is often seen in the field, and the plants came to maturity in a normal manner although greatly stunted on low yielding pots and always considerably smaller than plants in the field.

The first crop grown was soybeans; the season of 1918 was unfavorable, and the pots had to be watered with rather hard tap water. Either on account of the slight amount of calcium carbonate thus supplied, or because the soil was not as acid as had been thought, the unlimed pots bore quite as good a crop as those limed. Following the first crop of soybeans, it was decided to grow a

cereal crop naturally high in silica, and the choice fell on oats. The treatment with fertilizers, i.e., nitrogen, potassium and soluble phosphorus only, was repeated. No additions of silica were made to any of the pots. The oats grown in 1919 suffered from the depredations of mice, which ate the seeds before they germinated, so that certain pots had to be replanted. Pots 9 and 10 in row 15, and 6 to 10 in row 33 were replanted, some a third time. Yields were doubtless affected by the later planting. The pots were watered with tap water to some extent, but not so much as in 1918. The difficulties encountered with the oats led to the choice of soybeans again for the third crop. A second application of all the various treatments was made at the same rates as when first used, with the exception of calcium carbonate, which was applied at half the former rate. The season of 1920 was exceptionally favorable for soybeans, as may be seen from the large yields of the pots. Rains were regular during the growing season, and the pots were not artificially watered at any time. For that reason, perhaps, or possibly on account of the very rapid depletion of calcium from soils in cylinder experiments, as noted by Mooers (11), the yields from the pots without additions of basic materials are very small. The plants in pot 9, row 13, shed their leaves prematurely, so that the yield recorded was mostly stems, a circumstance reflected in the high silica and low phosphorus content of the crop from this pot. There were no pods borne on these plants, but those on pot 10 of the same row had a few. Buckwheat was the last crop grown, in 1921. It made a satisfactory growth on all the pots except those without lime or slag. On these, the seed germinated in a normal manner, but the plants grew scarcely at all. When the other plants had matured seed and were harvested, only a few stunted plants were still alive on these pots. The weights of dried crop secured were too small even to furnish samples for analysis. The crop suffered somewhat from dry weather, but was not artificially watered. The plants bloomed profusely but seed production was quite light.

ANALYTICAL METHODS

Grain and straw were always ground together in preparing the samples for analysis. Total silica was determined by ashing 20 gm. of the finely ground sample in a platinum dish at the lowest possible temperature, finishing in an electric muffle furnace held at 500–550°C. The dishes were allowed to cool, covered, water and hydrochloric acid added and evaporated to dryness, finally baking at 120 to 130° to dehydrate silica. The residue was moistened with strong hydrochloric acid, diluted and digested until salts were in solution, and filtered on a retentive paper. The thoroughly washed silica was ignited in platinum, weighed, evaporated with 15 cc. hydrofluoric acid plus a few drops sulfuric acid, ignited and weighed again. Total silica is thus obtained by difference. Sand was determined in a similar manner, but instead of the separated silica being ignited, it was washed from the filter back into the dish, evaporated, 20–40 cc. 5 *N* sodium carbonate solution added and boiled

about 5 minutes, being kept covered while boiling. Some hot water and a few drops of strong sodium hydroxide solution were added, again brought to boiling, allowed to settle and carefully decanted onto the same filter. The residue in the dish was treated twice more with 20 cc. portions of the sodium carbonate, and was finally washed with water, then with dilute acid and finally thoroughly with hot water. The silica in this residue of "sand" was determined as previously described, and subtracted from total silica gives *plant silica.* In order to check the work, the soluble silica in the alkaline filtrates was determined directly in numerous cases. Good agreement was always obtained. The procedure described is the same in principle as the official method (2, p. 15); a slight modification was designed to shorten the method. Dilution after boiling with sodium carbonate solution is not mentioned in the official method, but was found essential with samples high in silica; if not done, the dissolved silica is likely to gelatinize on the filter, and thus cause much extra work if the determination is to be saved.

The determination of "plant silica" is not by any means perfect. The data obtained from the soybeans grown in 1918 gave rise to the suspicion that silica in sand had been appreciably attacked and was included with the plant silica, since the percentages of silica in sand were much higher than those obtained from the soybeans grown in 1920, while plant silica percentages were considerably higher and showed a tendency to vary with the sand. It should be noted that the sodium-carbonate-insoluble silica is not all supplied by sand. Under the microscope, sand grains were almost absent from some of the residues. The bulk of the material was very fine and from the nature of the residue left after treatment with hydrofluoric and sulfuric acids, it was judged to be of clayey nature. The fact that it was much less in 1920 is due to the frequent rains of that season, which both washed the leaves of the plants and reduced windblown soil to a minimum. It is possible to employ a correction formula, after the plan of Dyer (6), to allow for silica dissolved from sand, and to do so seems to improve the data. One such formula, founded on the assumption that only 75 per cent of the extraneous silica was obtained as sand, appeared to fit the data obtained from both the 1918 and 1920 crops of soybeans very well and made the results quite concordant. The percentage of plant silica in the two crops of soybeans contained in table 1 are calculated on this basis, i.e., the percentages of plant silica as indicated by the analytical data are *decreased* by one-third the amount of silica insoluble in sodium carbonate solution. The same procedure applied to the data obtained from analyses of oats, however, causes no improvement, nor indeed is it to be expected that the same formula could apply in both cases. The oats plant is much higher in total and sodium carbonate soluble silica, and the consequent difficulty in dissolving all the plant silica would tend toward low results, rather than high for sodium carbonate soluble silica. Furthermore, the ash of oats plants contains practically no carbonate, while soybean-plant ash is high in carbonate, a factor which can hardly be without influence on the amount of extraneous

silica attacked during the ignition, in spite of all precautions to keep the temperature low. For these reasons, it is thought that analytical errors due to attack of sand and resistance of plant silica are more nearly balanced in the data for oats, and the percentages of plant silica in the crop tabulated are those actually obtained. The buckwheat is so low in silica that no effort at correction seems advisable. In all cases, the percentages of "sand silica" tabulated are those actually found by analysis.

Total phosphorus was determined by the official method (2, p. 18) and weighed as magnesium pyrophosphate.

DISCUSSION OF DATA

The yields in grams of air-dry crop (all parts above ground) and percentages of silica insoluble in 5 *N* sodium carbonate solution (sand silica) and soluble in that reagent (plant silica) and total phosphorus in the crops grown in the pots, are presented in table 1. The only reason for tabulating the percentages of extraneous silica (sand) is the possible influence of variations in this constituent upon the figures obtained for plant silica, as has been explained. To facilitate discussion of the effects of the different treatments, each is designated by a letter in the table.

The effect of treatment with blast furnace slag will be first discussed. A comparison of data from treatments A, B and G, rock phosphate (floats) and blast furnace slag with and without calcium carbonate, and phosphate and carbonate together, does not indicate that slag is inferior to precipitated carbonate with respect to weights of crop produced. The slag has supplied sufficient base. Data for plant silica in both crops of soybeans indicate that the slag has supplied a considerable amount of silica, which has been assimilated by the soybeans. Variation between duplicate pots is too great with the oats, and there is no suggestion of a similar effect with the buckwheat. On the other hand, buckwheat is the only crop furnishing data which suggest that the slag has been of any aid in the utilization of the phosphorus of rock phosphate. This effect seems apparent only in the absence of calcium carbonate, and unfortunately the crop failed on the pot (E) without slag or carbonate, so that there is no indication of how much phosphorus the plant might have taken up from the raw phosphate in the absence of both basic materials.

The treatments C, D and L are identical with those just discussed, aside from the substitution of the soluble monocalcium phosphate for the rock phosphate. With one or two exceptions, the largest yields were obtained from the treatment C with both slag and calcium carbonate. The availability of the silica in slag is again indicated, but calcium carbonate has reduced the amount assimilated. All crops after the first have given decisive indications of the ready availability of the soluble phosphate supplied, but there is no evidence that the silica in slag had any effect upon this.

The yield of soybeans from the first crop grown in 1918, on the pots receiving the treatments which have been discussed and considering treatments E and F

TABLE 1

Yields, silica in "sand," "plant silica" and phosphorus in crops

ROW NUMBER	POT NUMBER	TREATMENT	SOYBEANS, 1918				SOYBEANS, 1920				OATS, 1919				BUCKWHEAT, 1921			
			Crop	Silica		Phosphorus	Crop	Silica		Phosphorus	Crop	Silica		Phosphorus	Crop	Silica		Phosphorus
				Sand	Plant			Sand	Plant			Sand	Plant			Sand	Plant	
			gm.	*per cent*	*per cent*	*per cent*	*gm.*	*per cent*	*per cent*	*per cent*	*gm.*	*per cent*	*per cent*	*per cent*	*gm.*	*per cent*	*per cent*	*per cent*
13	1	A: Floats, blast furnace slag, $CaCO_3$.	83	0.34	0.25	0.17	231	0.16	0.21	0.14	106	0.69	1.79	0.24	74	0.18	0.12	0.16
13	2		66	0.60	0.18	0.11	269	0.11	0.23	0.17	102	0.44	1.32	0.21	74	0.20	0.12	0.14
13	3	B: Floats, blast furnace slag.	78	0.44	0.32	0.12	241	0.13	0.24	0.19	103	0.41	1.59	0.22	59	0.22	0.11	0.19
13	4		80	0.57	0.31	0.12	217	0.12	0.24	0.19	108	0.54	1.65	0.23	72	0.20	0.13	0.18
13	5	C: Soluble phosphate, blast furnace slag,	90	0.57	0.20	0.15	313	0.13	0.24	0.25	126	0.52	1.31	0.26	84	0.15	0.09	0.30
13	6	$CaCO_3$.	104	0.44	0.16	0.17	370	0.13	0.20	0.25	135	0.48	1.35	0.28	84	0.13	0.09	0.29
13	7	D: Soluble phosphate, blast furnace slag.	75	0.58	0.23	0.12	321	0.13	0.26	0.25	98	0.62	1.74	0.25	75	0.16	0.11	0.31
13	8		90	0.52	0.30	0.14	313	0.11	0.26	0.26	63	1.40	1.60	0.31	82	0.21	0.12	0.28
13	9	E: Floats.	85	0.54	0.26	0.19	18	0.65	0.23	0.19	56	1.07	1.40	0.32	4			
13	10	F: Soluble phosphate.	92	0.63	0.24	0.16	31	0.27	0.18	0.26	83	0.40	1.37	0.23	5			
15	1	G: Floats, $CaCO_3$.	95	0.64	0.10	0.18	178	0.15	0.11	0.21	79	0.45	1.20	0.24	76	0.26	0.14	0.15
33	10		77	0.49	0.11	0.16	313	0.15	0.15	0.17	56	0.70	1.71	0.33	60	0.21	0.12	0.15
15	2	H: Floats, $CaSiO_3$, $CaCO_3$.	123	0.55	0.16	0.21	178	0.18	0.21	0.19	102	0.85	1.62	0.29	73	0.21	0.09	0.16
33	9		82	0.43	0.25	0.16	311	0.14	0.26	0.18	79	0.57	2.19	0.30	75	0.19	0.14	0.17

15	3	I: Soluble phosphate hydrated silica, $CaCO_3$.	102	0.46	0.31	0.18	238	0.14	0.28	0.24	109	0.49	1.79	0.25	73	0.23	0.09	0.29
33	8		112	0.39	0.23	0.18	177	0.19	0.27	0.24	87	0.72	1.72	0.30	85	0.26	0.15	0.30
15	4	J: Soluble phosphate, $CaSiO_3$, $CaCO_3$.	101	0.72	0.30	0.19	284	0.13	0.26	0.20	87	0.74	1.83	0.33	80	0.52	0.16	0.28
33	7		131	0.46	0.23	0.15	251	0.68	0.31	0.22	99	0.45	2.03	0.28	85	0.23	0.12	0.31
15	5	K: Soluble phosphate, water glass, $CaCO_3$.	85	0.64	0.33	0.18	303	0.36	0.29	0.27	99	0.38	1.80	0.29	81	0.18	0.08	0.35
33	6		123	0.32	0.24	0.20	244	0.18	0.34	0.25	93	0.35	1.85	0.29	68	0.27	0.10	0.29
15	6	L: Soluble phosphate, $CaCO_3$.	97	0.59	0.18	0.16	258	0.14	0.15	0.24	74	0.73	1.07	0.30	72	0.29	0.06	0.35
33	5		110	0.45	0.16	0.16	312	0.18	0.12	0.24	88	0.50	1.30	0.31	73	0.27	0.09	0.25
15	7	M: Hydrated silica, $CaCO_3$.	96	0.73	0.25	0.17	230	0.14	0.26	0.20	70	1.26	1.90	0.31	31	0.33	0.12	0.09
33	4		99	0.58	0.21	0.19	279	0.15	0.20	0.20	81	0.53	1.83	0.30	53	0.25	0.09	0.12
15	8	N: $CaSiO_3$, $CaCO_3$.	88	0.78	0.18	0.16	218	0.14	0.27	0.15	96	0.91	1.60	0.26	50	0.20	0.08	0.11
33	3		106	0.58	0.20	0.21	300	0.15	0.23	0.21	95	0.54	1.63	0.28	76	0.22	0.10	0.15
15	9	O: Water glass, $CaCO_3$.	67	0.66	0.27	0.13	178	0.14	0.35	0.20	88	0.54	1.86	0.26	51	0.40	0.21	0.31
33	2		104	0.38	0.21	0.19	244	0.18	0.30	0.23	134	0.38	1.72	0.23	79	0.22	0.13	0.16
15	10	P: $CaCO_3$.	77	0.79	0.08	0.14	171	0.16	0.15	0.15	50	0.60	1.26	0.24	35	0.29	0.11	0.09
33	1		79	0.54	0.14	0.18	286	0.15	0.13	0.18	99	0.43	1.42	0.26	41	0.23	0.10	0.12

which had no additions of basic material, give some reason for the belief that the slag may have had a slightly unfavorable influence the first season. This is not apparent in later crops, although a second full application of slag and half application of calcium carbonate were made preceding the soybeans grown in 1920.

The effect of the lack of basic materials in treatments E and F began to be noticeable at the second crop, and caused a practical failure at the fourth crop. Pots receiving slag as the only basic material compare well with those receiving calcium carbonate, although the latter was applied in larger amount. Data obtained from this experiment indicate that slag is an effective substitute for calcium carbonate; there is little evidence that it has a favorable effect in any other respect.

The treatments G and H, rock phosphate and calcium carbonate alone and with the addition of calcium silicate were intended to indicate whether a silicate presumably more active than slag would have a similar effect when used in connection with rock phosphate. Yields of the first and second crops appear to have been increased by the calcium silicate. The plant silica content of all the crops excepting buckwheat appears to have been appreciably increased by this substance. The phosphorus content of crops has been slightly increased in several instances where the silicate was used.

The treatments J and L are similar, save that the phosphorus was in a soluble form. Again the yields are slightly increased by calcium silicate in the greater number of instances; plant silica is considerably increased in all cases, but the effect on phosphorus is not plainly indicated.

In the treatments N and P, calcium silicate and carbonate and carbonate alone, we have another opportunity to note the effect of calcium silicate, this time when used without any phosphorus carrier. The averaged yield of the pair of pots on which the silicate was used is larger than the yield where carbonate only was applied. The plant silica content is higher except in the case of buckwheat, and the averaged percentages of phosphorus are slightly higher.

Sodium silicate (water glass) was the source of silica for two treatments, K with soluble phosphate and calcium carbonate, and O with calcium carbonate only in addition to the sodium silicate. Comparing these with the pair of pots P, which received calcium carbonate only, it is seen that K has usually borne the largest crops, as would be expected from the fact that this treatment included available phosphorus. The crop from these pots has likewise been highest in phosphorus. The silica of water glass has been absorbed to a considerable extent by both soybeans and oats, apparently but little by buckwheat, unless the figure for plant silica in the crop from pot 9 in row 15 is accepted. The determinations on the sample from both this pot and its duplicate were repeated, but the same results were obtained. The effect of the water glass upon the phosphorus content of the crop from the pots without phosphorus treatment is not definitely indicated. Soybeans of 1918

indicated no effect, as did oats in 1919, save that the crop was larger where water glass was applied. Soybeans of 1920 indicated a marked increase in phosphorus content, and the buckwheat a remarkable increase, but the high figure is again dependent upon a sample which gave abnormal results for another constituent.

The treatments with silicates discussed have been complicated somewhat by the extra base introduced by the silica carrier. The treatments I and M were designed to show the effect of silica itself. Hydrated silica, prepared by acidifying and evaporating water glass and washing the precipitate, and dialyzed silica in addition, were applied to these pots, together with calcium carbonate, and in one case, soluble phosphate. Except with soybeans in 1920, treatment I, including phosphate, has yielded most crop. In the other years, the hydrated silica has shown practically no effect upon yields as compared with the effect of calcium carbonate alone. The silica offered in this form has been assimilated, as is shown by a comparison between the composition of crops from pots so treated and from those pots having treatment P, calcium carbonate without added silica. An inspection of the data for phosphorus content of the crops from the pots discussed would seem to indicate that the added silica has resulted in a slight increase in phosphorus content of every crop except buckwheat.

SUPPLEMENTARY TEST FOR COMPARISON OF SILICATES WITH CARBONATES

This was started in 1914, and conducted in 20-inch sewer pipe cylinders in a manner similar to the test which has been described. The comparison included sulfur as a part of the treatment on several pots, as it was thought that the sulfur content of slag might be responsible for some of its beneficial action. The pots treated with powdered sulfur at the rate of 5 gm. each will not be considered, as the yields fell off very rapidly, evidently on account of the increasing acidity. Pot 10 received two much smaller applications of sulfur the first and second years of the test, none thereafter, but was fertilized the third season. The soil was of the same type as that employed for the experiment previously described, but was taken from a slope long uncultivated and was found to have an appreciably greater reserve supply of bases. The blast furnace slag and other materials were from the same lots as those used in the other experiment described; the slag was ground to pass a 100-mesh sieve. In this case, slag, silicate and carbonate were applied at the same rate, 100 gm. per pot, equivalent to 4400 pounds per acre. The fertilized pots received 3 gm. dried blood, 1.5 gm. potassium chloride and 1.7 gm. calcium phosphate each. The phosphate used was the dibasic salt.

Yields and, in some cases, phosphorus contents of crops from these pots are presented in table 2. The first crop of red clover gave the largest yield on the pots treated with calcium silicate, but the second cutting was largest on the slag treated pots. The total produced for the season averaged nearly the same on each pair of pots, fertilized and unfertilized together.

TABLE 2

Air-dry weights and phosphorus content of crops in supplementary test, Row 19

POT	TREATMENT	RED CLOVER, 1914–1915		WHEAT, 1915–1916						SOYBEANS, 1917		SOYBEANS, 1918	OATS, 1919	SOYBEANS, 1920	BUCKWHEAT, 1921		TOTAL CROP, SEVEN YEARS
				Grain		Straw		Plant									
		First cutting	Second cutting	Crop	Phosphorus	Crop	Phosphorus	Crop	Phosphorus	Crop	Phosphorus	Crop	Crop	Crop	Crop	Phosphorus	
		gm.	*gm.*	*gm.*	*per cent*	*gm.*	*per cent*	*gm.*	*per cent*	*gm.*	*per cent*	*gm.*	*gm.*	*gm.*	*gm.*	*per cent*	*gm.*
1	Check	137	70	55	0.43	96	0.09	151	0.22	93		66	49	71	10		647
10	Sulfur, fertilizer later	158	50	69	0.42	129	0.09	198	0.20	65		48	59	39	3		620
2	100 gm. slag	181	72	80	0.41	140	0.07	220	0.20	155	0.18	137	69	185	47	0.15	1066
3	Same with fertilizer	195	89	75	0.42	122	0.07	197	0.20	148	0.22	140	81	185	86		1121
4	100 gm. $CaSiO_3$	204	90	102	0.41	200	0.08	302	0.19	134	0.20	115	98	144	35	0.18	1122
5	Same with fertilizer	195	52	81	0.42	142	0.07	223	0.19	145	0.20	110	86	184	15		1010
8	100 gm. $CaCO_3$	148	62	68	0.43	119	0.12	187	0.23	130	0.17	104	61	270	37	0.15	999
9	Same with fertilizer	142	42	52	0.44	86	0.11	138	0.24	102	0.17	94	42	308	22		890

Calcium silicate seems to have been of most benefit to the wheat harvested in 1916; the phosphorus contents of the wheat are found to have an inverse relation to the yields, which are lowest on the pair of pots treated with calcium carbonate, but the crops grown on these pots carry the highest percentage of phosphorus.

Previous to planting the 1917 crop of soybeans, the pots were given another application of basic materials at the same rate as at the beginning. The formula for the application of fertilizer was changed, thus: dried blood, 2.5 gm.; sodium nitrate, 0.5 gm.; dibasic calcium phosphate, 2.7 gm., and potas-potassium chloride, 1.2 gm., were applied dry to each pot. Slag appeared to be of greatest benefit to soybeans, with calcium silicate next best. The connection between yields and phosphorus content of the crop noted in the case of the wheat was not apparent in the soybean crop. The indications of the soybeans grown in 1918 were practically the same as given by the crop of the previous season; yields were less, however.

The slight increases or, quite commonly, marked decreases in the crop attributable to fertilization of these pots caused the abandonment of this part of the program. After 1917, no fertilizer was applied. The oats crop of 1919 did best on the pots treated with calcium silicate; the slag treated pots were next best. The soybeans grown in the exceptionally favorable year of 1920 gave a surprising yield on the pots receiving calcium carbonate, far better than that obtained from the pots receiving silicates, which yielded about the same. The next crop, buckwheat grown in 1921, saw the slag treated pots again the best yielders, but calcium carbonate was second. The check pots, which had been gradually declining in yield, were nearly complete failures in 1921. Number 10, which had received sulfur the first two seasons, made the poorest showing. The total weight of crop produced in 7 years is nearly the same for blast furnace slag and calcium silicate. Calcium carbonate was apparently more beneficial in the later years of the test than it had been at first, but in total weight of crops the two pots treated with carbonate are distinctly inferior to those receiving the silicate and blast furnace slag.

RESULTS OF FIELD TEST OF SLAG AND LIMESTONE

The agronomy department at this Station has conducted an investigation of the influence of various factors upon the physical characteristics of the wheat plant. Included in this work are two small plots, one dressed with slag at the rate of 6000 pounds per acre and the other with commercial ground limestone at half the above rate. In addition to the disparity in size of application, the factor of fineness of material also was probably in favor of the slag, as it was ground to pass a 20-mesh sieve, and 56 per cent of the material passed a sieve having 100 meshes per linear inch. The mechanical analysis of the limestone is not definitely known, but it was certainly coarser than the slag, since screen separation of similar lots of stone from the same source showed that 95 per cent or more passed 10 mesh and only 30 to 40 per cent passed 100 mesh.

Small samples of mature wheat plants were taken from these plots, dried and after determining the amount and characteristics of the grain, the whole sample of grain and straw together was ground for analysis. The results of the analytical work are presented in table 3, together with acre yields based on single plots 10 feet square. The yields recorded would indicate that the slag had been beneficial. No explanation is offered for the low yield on the plot receiving limestone. The percentage relation of grain to the whole plant above ground is lowest in the case of the slag treated plot. The weights of 50 grains tabulated indicate that grain from this same plot is least well developed. The low percentage of phosphorus in the plants from this slag treated plot is doubtless connected with the smaller proportion of grain in the whole plants, and might lead to the belief that a part of the grain had been lost, but the fact that the grain from this plot is lightest does not support this explanation.

TABLE 3

Yields and composition of wheat plants from slag, limestone, and check plots

TREATMENT	YIELD PER ACRE	GRAIN IN SMALL SAMPLES	WEIGHT OF 50 GRAINS	SILICA		PHOSPHORUS
				In sand	In plant	
	bus.	*per cent*	*gm.*	*per cent*	*per cent*	*per cent*
Check	18.1	25.5	1.27	0.30	2.11	0.213
Slag	21.1	19.8	1.14	0.35	2.80	0.176
Limestone	12.6	23.0	1.17	0.32	2.32	0.212

On the whole, it does not seem unreasonable to suppose that the large application of finely ground slag to the soil has resulted in an excess of nitrogen being made available. This would result in a greater vegetative growth, both by stooling and by the formation of straw, with but a slightly larger total yield of grain not well filled out. The wheat plants from the plot treated with slag are highest in plant silica, but the data do not indicate that this silicate has aided in the assimilation of phosphorus and thus tended toward improvement in quality of the grain.

SUMMARY

In this paper are reported the results of two series of pot experiments and one field experiment on small plots, designed to determine the effect of blast furnace slag and other silica carriers with reference to supply of bases to the soil and aid in assimilation of phosphorus. Data from which conclusions have been drawn have included yields and chemical composition of the plants grown.

One series of pot experiments included thirty 20-inch cylinders with sixteen treatments, and was designed to show the effect of silica applied in various forms to an acid silt loam soil with and without calcium carbonate, rock phosphate or soluble calcium phosphate. Data from two crops of soybeans and one each of oats and buckwheat are available for drawing conclusions,

which may be summarized as follows: Silica, added as air-dry hydrated silica plus dialyzed silica, blast furnace slag, calcium silicate and sodium silicate, was assimilated, as shown by increased percentages of plant silica in the crops. The silica was generally increasingly available from the compounds in the order given. Buckwheat showed smallest differences in silica content as the result of treatment, oats the greatest. Additions of calcium carbonate usually appeared to lessen the amounts of silica taken up by the plants.

Ground blast furnace slag is an effective source of bases and its silica is to some extent assimilated, but conclusive evidence that the silica thus added to the plant is of use in enabling the plant to utilize more phosphorus from rock phosphate was not obtained. Except for buckwheat, calcium silicate is also an effective source of silica. The silica from this source appeared to enable most of the crops to obtain more phosphorus, when that element was added as rock phosphate.

Pots treated with various silica compounds and soluble phosphates furnished no data on which to base conclusions as to the action of silica in phosphorus assimilation. A majority of the pots to which additions of silica compounds with calcium carbonate were made showed increased yields and phosphorus content in the crop as compared with pots receiving calcium carbonate only, the soil being the sole source of phosphorus.

A second series of eight cylinders, similar to those described, furnish a comparison of the effects of equal weights of slag, precipitated calcium silicate and carbonate, with and without a complete fertilizer. Seven crops were grown on this series of pots and with the exception of one season, yields on the pots to which the silicates were applied were greater than yields from check pots or those receiving carbonate.

Benefit from calcium carbonate was unmistakable only after the second year, but became increasingly noticeable with time. Of the three crops from which samples were analyzed, only the soybeans showed any consistent relation between silica and phosphorus utilization. With this crop, the plants were higher in phosphorus on those pots where silicates were used instead of carbonates. The wheat crop indicated that the opposite was the case, but low yields accompanied the high phosphorus percentages.

A field test in which finely ground slag applied at the rate of 3 tons per acre was compared with half as much limestone, probably somewhat coarser, on wheat indicated that the slag caused a slightly larger yield of less well developed grain. This is thought to be due to a more abundant supply of available nitrogen on the plot to which the slag was applied. The slag caused a considerable increase in the silica content of the wheat plant, but phosphorus was decreased.

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THE SULFUR CONTENT OF RAINWATER

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Improved methods of sulfur analyses for soils and crops have revealed the necessity of studying the rôle which sulfur fertilizers may play in any system of permanent soil fertility. That sulfur is added to the soil in the rain and snow was recognized by early investigators, but the agricultural importance of this means of sulfur supply will depend largely upon the amount of sulfur found in rainwater falling in rural communities. Unfortunately most of the data relating to this subject have been obtained from analyses of rain falling in towns and cities.

Perhaps the earliest work on the analyses of rain for sulfur content is reported by Smith and summarized by Lawes, Gilbert and Warrington (10) as follows:

LOCALITY	H_2SO_4	POUNDS PER ACRE*	
		SO_3	S
	p.p.m.		
England, country inland	5.52	34.54	13.82
England, towns	34.27	214.70	85.88
Scotland, country seacoast	5.64	35.31	14.12
Scotland, country inland	2.06	12.89	5.16
Scotland, towns	16.50	103.32	41.33
Scotland, Glascow	70.19	439.77	175.91

* These figures were calculated on the basis of the data furnished by Lawes, Gilbert and Warrington that 2.41 p.p.m. of water amounted to 18.5 pounds per acre of SO_3.

Lawes, Gilbert and Warrington (11) found that the sulfuric acid (SO_3) contained in the rainwater at Rothamsted averaged for two years (1881–83) 2.41 parts per million of water amounting to 18.5 pounds per acre per annum. Hall (5) and Miller (13) made a summary of results from 1881–87 on the analyses of rainwater at Rothamsted and showed that the total amount of sulfur (SO_3) added yearly per acre was 17.41 pounds. Miller also reported that Gray found a yearly average of 14.94 pounds of sulfur (SO_3) per acre in the rainwater at Lincoln, New Zealand, and that Sestini found 20.89 pounds of sulfur (SO_3) in the precipitation at Catania, Sicily.

Crowther and Ruston (3) made a very extensive study of the rainwater falling at eleven different stations in the city of Leeds, England. The amounts of sulfur (SO_3) per acre varied from 91 pounds in the suburban residential section to as much as 336 pounds in the industrial area. At Garforth, six miles east of Leeds, they found an average annual precipitation of sulfur equivalent to 95.7 pounds SO_3 per acre. Later Crowther and Stewart

[1] The writer wishes to express his thanks to Dr. P. E. Brown for reading the manuscript.

(4) made further studies on the sulfur content of rain and reported results for 1912–1913 at Garforth to be 60 pounds, while in the polluted area of Leeds 352 pounds of sulfur (SO_3) per acre were obtained.

Wituynj (19) estimated the amount of sulfur in monthly samples of rainwater collected at eight different places in Russia from April, 1909–March, 1910. The results varied from 5.13 to 70.88 pounds of sulfur (SO_3) per acre, the larger amounts being obtained in the rain from the cities of St. Petersburg, Ochta and Mariupol. Kossovich (9) concluded from his studies that data for European Russia and available data for other countries indicated that the sulfur content varied between 8.92 pounds in the country and 72 pounds per acre per annum in the neighborhood of towns and industrial work, where the greatest portion falls in the winter.

Hart and Peterson (6) analyzed the rain falling at Madison, Wisconsin, from June, 1910, to October, 1910, and found the total amount of sulfur (SO_3) brought to an acre in five months was 10.7 pounds. They estimated a yearly fall of not less than 17 or 18 pounds.

Numerous analyses of rain and snow have been made at Mt. Vernon, Iowa, which may be summarized as follows:

INVESTIGATOR	PERIOD	RAINFALL	SO_3 PER ACRE
		inches	*lbs.*
Knox, W. K. (8)	Apr. 28, 1912–June 4, 1912	7.45	0.129
Artis, B. (1)	Oct. 12, 1914–June 9, 1915	18.49	4.913
Peck, E. L. (14)	Oct. 20, 1916–June 8, 1917	17.69	8.435
Trieschmann, J. E. (17)	Oct. 1, 1918–June 15, 1919	22.25	1.509
Shaffer, S. (15)	Aug. 18, 1920–June 1, 1921	20.97	327.0619

These data show that there is a wide variation in sulfur content of rain and snow from year to year. In the case of 1920–1921 the results are extremely high, and there is reason for belief that some discrepancy might exist in the calculations, because a comparison of the other substances reported by this investigator check fairly closely with the results of the previous investigators.

MacIntire, Willis and Holding (12) reported that the average analyses of three years' rainfall at Knoxville, Tennessee, showed an annual precipitation of 124 pounds of sulfur trioxide or 49.6 pounds of sulfur per acre.

Stewart (16, p. 107) reported as an average of seven years' work at Urbana, Illinois, that 45.1 pounds of sulfur was added to an acre annually and found that the amount of sulfur collected depended upon the amount of precipitation. Wilson (18) found that the rainwater collected at Ithaca, New York, supplied the soil with an average of 26.19 pounds of sulfur per acre annually.

The investigations reviewed show conclusively that the amount of sulfur reaching the soil through precipitation varies greatly with respect to the proximity of the sampling station to cities or towns. In order to study this means of the addition of sulfur to the soil under actual farm conditions, the writer placed a rain gauge on the agronomy farm of the Iowa Agricultural Experiment Station, which is two miles south of Ames. The results of the analyses of rain and snow for the year 1921 are reported in this paper.

Samples of rain and snow were collected in a 4-gallon glazed-stone crock placed close by a metal rain gauge of the U. S. Weather Bureau standard type. During the spring and summer months the crock was covered with two thicknesses of fine muslin between which was a large filter paper, to exclude particles

of soil and other foreign material carried by the wind. The samples were stored in glass bottles and sealed with paraffined glass stoppers. Each month's samples were analyzed separately with the exceptions of January and February and November and December.

Sulfur in rainwater may occur chiefly as hydrogen sulfide, sulfur dioxide or sulfur trioxide. A method for total sulfur would necessarily require some oxidizing mixture to convert all the sulfur to the sulfate form. In this laboratory Benedict's (2) method for total sulfur in urine, with a few modifications, was found very accurate and convenient for the analysis of rainwater. Denis' sulfur reagent, as suggested by Hawk (7), was used instead of that employed by Benedict because it was easier to bring the solution to dryness during the last stage of evaporation. The method is as follows:

Five cubic centimeters of Denis' reagent are added to 250 cc. of rainwater and portions of this solution are placed in an 80-cc. porcelain evaporating dish heated on an electric hot plate. When the 250 cc. have been evaporated to dryness the dish is placed in an electric furnace and heated to redness for 10 minutes after the black residue has become dry. After cooling, 10–20 cc. of dilute (1:4) HCl are added to the residue in the dish which is warmed gradually until the contents have completely dissolved. The solution is filtered into a small Erlenmeyer flask and washed with cold distilled water to about 150 cc. The flask is placed on the electric hot plate, heated to boiling, and 10 cc. of 10 per cent $BaCl_2$ solution added drop by drop (5 cc. per minute), and allowed to stand overnight. The precipitate is filtered into weighed Gooch crucibles and washed free of chlorides with cold water (150 cc. in 15 cc. portions). The crucibles are dried at 110–120°C. for one hour and weighed. Controls should be run on the oxidizing mixture.

TABLE 1

Rainfall and content of sulfur for 1921

MONTH	RAINFALL	SULFUR CONTENT	
		SO_3	S
	inches	*lbs. per acre*	*lbs. per acre*
January and February	1.00	5.04	2.02
March	1.28	3.74	1.50
April	2.91	5.49	2.20
May	2.83	4.57	1.83
June	4.77	2.67	1.07
July	1.11	1.00	0.40
August	7.35	5.47	2.19
September	6.76	3.77	1.51
October	1.25	3.67	1.47
November and December	1.12	1.75	0.70
Totals	30.38	37.17	14.89

The results secured from analyses of rain and snow for total sulfur content from January 1 to December 31, 1921, are given in table 1. On account of the small precipitation it was necessary to combine the samples for January and February and also November with the December rain.

An examination of the data in the foregoing table shows for the year 1921 that there was a total rainfall of 30.38 inches, which is considered about normal for this section of Iowa. The sulfur content averaged for the year 3.32 parts per million parts of water. The total amount of sulfur brought to an acre of soil was 14.89 pounds, or an average monthly addition of 1.24 pounds per acre. With but few exceptions, the amounts of sulfur are fairly constant for each month, and there is no evidence whatever that the sulfur content depends directly upon the amount of precipitation.

It is believed that about 15 pounds of sulfur per acre per annum will represent a generally correct figure for rural communities. While this work reports only one year's data, the investigations at Rothamsted and other places show that the amount of sulfur added in the rainwater does not vary greatly from year to year.

The one conclusion to be drawn from this work is that under actual farm conditions the quantity of sulfur added to the soil per annum in the rainwater is not sufficient to overbalance the loss by drainage and cropping.

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SOIL EXPERIMENT FIELDS AND THEIR VALUE

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The chief purpose of this paper is to give a little of the historical background for soil experiments, to call attention indirectly to the value of such tests as have been conducted in the past, and to illustrate certain important phases of such work by the results of experiments on Iowa soils. It has not been deemed necessary to go into the value of the work done in the past, to any large extent, for a mere reference to the experiments is sufficient in most cases to lead to very definite conclusions regarding their value. It may be said however, that if any consideration at all is given to the importance of making soil experiments of interest and value to farmers, the importance of field tests is certainly evident, and if the farm practices of today are compared with those of a few years ago, the value of the work which has so completely changed many farming operations is seen to be very great.

HISTORICAL

The details of the earliest field experiments on soils lie buried in the mists of antiquity but a study of agricultural history leads to the conclusion that such experiments have probably been carried out in a rude way from time immemorial.

The writings of Moses indicate that agriculture is as old as man and while specific information regarding the practices followed is lacking, it would seem that Isaac and Jacob, and probably Abraham also, tilled their fields and raised their crops by methods which they had found by experience and comparison to be the best. Apparently Isaac knew how to grow corn for it is said he reaped an hundredfold. What is more reasonable than to conclude that he learned by field experiments how to secure such large yields?

The first definite record of the application of manures to soils appears in the agricultural literature of the Greeks. Pliny ascribes the "invention" of manures to the Grecian king, Augeas. In Homer, an old king is found manuring his field with his own hands. These legends may very well be interpreted to mean that the value of manure was discovered through field experiments. Theophrastus, a disciple of Aristotle and often called the father of botany, wrote on the history of plants and his work contains many interesting observations on soils and manures. He enumerated six different kinds of manures and stated that a mixture of soils (sand with clay and vice

versa) produced the same effects as manures. Would it not be quite logical to conclude that he had tested the accuracy of this statement in field experiments? Perhaps he and neither Abraham nor the Grecian king was the first soil experimentalist.

Much of the knowledge of this early period of the world's history is based upon conjecture and the speculations indulged in here are at least supported by as much of fact and definite evidence as the conclusions reached by historians along many other lines. Sufficient has been said to indicate that very early in the history of the world field experiments were probably an integral or at any rate a casual part in the operations of the leading agriculturists.

With the advent of the group of learned Romans who were interested in agriculture and whose writings form the foundation of all agricultural literature, conjectures are replaced by rather definite information, mere opinions by facts. The rise of the Roman Empire wrought fundamental and far-reaching changes throughout a large part of the world and in all phases of human activity. Agriculture along with the other arts and sciences was affected to only a slightly less extent than were governments, society and general living conditions. Indeed from the writings of Cato, Varro, Columella, Virgil, Pliny and Palladius it would appear that agriculture passed from the stage of an occupation to an art and perhaps even became a "fad" to some extent. De Re Rustica, the oldest Roman work on agriculture tells of the use of manure, of the plowing under of lupines as green manures, of the application of burned lime, and of the utilization of marl in Britain and Gaul with beneficial effects on the growth of crops. This information and much else of interest and value to farmers could have been secured only through the carrying out of field tests. There can be no question but that many tests were conducted on Roman farms to the lasting benefit of the art of agriculture.

The literature of this period and that of mediaeval times is not only filled with practical suggestions but it also contains many ingenious speculations, some of which have been found, by later work, to be sound and others of which have been shown to be fallacious. But it is not intended to consider here the various theories of soil fertility which have been suggested nor the development of our knowledge of the nutrition of plants. These have come as a result of the activities of the agricultural chemists whose investigations followed close upon the speculations of the Roman and mediaeval eras. Under their leadership agriculture entered upon a new and intensive period of development. Then there began the real experimental work, the results of which have formed the basis for the extensive investigations of recent years.

The years of activity on the part of the agricultural chemists have been divided into two main periods by Russel, characterized as The Search for the Principle of Vegetation, 1630–1750, and The Search for Plant Nutrients, 1750–1860. The latter period is subdivided into the Phlogistic Period, 1750–1800, and the Modern Period, 1800–1860. Passing over the earlier years, which were characterized by the brilliant investigations of such well-known scientists as Glauber, Jethro Tull, Francis Home, Priestley, Ingen-Housz, de Saussure, Davy and numerous others, all of whom carried on their studies in the laboratory or in small pots, it appears that, in 1834, Boussingault began a series of field experiments on his farm at Bechelbronn in Alsace—the first really scientific field tests. These experiments of Boussingault were so comprehensive and yielded results which were so striking that they have become almost classic. If the idea of field tests in ancient times cannot be accepted, at least it is certainly unnecessary to look further than Boussingault's work for evidence in support of the theory of their value. Perhaps the earlier studies in Palestine, in Egypt, in Greece and in Rome should not be dignified by the title of experiments but no one can question the experimental nature of Boussingault's investigations. An interesting digression might be made here to consider just what constitutes an experiment, a trial, and a demonstration, but the question is not essential to the subject in hand.

Only a few years elapsed until the idea of field experimentation led to the establishment of the world-famous Rothamsted Experiment Station. A few experiments were begun in 1837, on the farm of Sir John Bennett Lawes, more were added in 1840 and in 1843, the experimental work was officially begun under the direction of Lawes and his associate, Sir James Henry Gilbert. The plan of these field studies was based upon the earlier laboratory and pot culture work of many investigators but was influenced to the largest extent by the work of de Saussure and by the theories of Liebig, just enunciated. Hence the work centered around the mineral constituents of plants and particularly nitrogen nutrition.

The scope of the experiments at Rothamsted is so well known that nothing need be said about it here except to emphasize the fact that so many problems of practical as well as technical value have been studied there that practically all of the soil investigations which have been carried on in recent years have been based upon or at least suggested by the Rothamsted work. These investigations have been carried on continuously from 1843 to the present time and their value becomes greater with each succeeding year. The idea of the value of long-time field experiments on soils which quite generally prevails at the present time, needs no further support than that given by the Rothamsted fields.

Nine years passed before the first German experimental field was established at Möckern (Leipzig) and many more years elapsed before the fields in this country were laid out; but the ideal for all field tests in each case has been to imitate the Rothamsted experiments with such modifications as are necessary to fit the local conditions.

THE PRESENT SITUATION

The idea of the value of the Rothamsted work has become so firmly implanted and as a consequence soil investigators have become so accustomed to accepting long-time field studies as the most desirable and conclusive of all experimental work, that it is somewhat of a shock to read in a recent publication (1) that "it is highly probable that no fertilizer experiment as ordinarily conducted is possessed of sufficient practical value to justify the large expenditure of money, time and energy involved." The statement is made as a result of studies of the Pennsylvania and Ohio field experimental data and from a consideration of the "enormous variability of all soils and plants." The question immediately arises whether or not the statement is warranted. It demands careful attention from all who are interested in field experiments. Is the money which the national and state governments put into such work being wasted? Have the teachings of the past decade been all wrong? Are the farmers, the legislators and the scientists all being deceived?

It is not intended here to defend the Ohio and Pennsylvania experiments, not to call attention to the various questions which have been answered by them and by many other field investigations particularly those at Rothamsted. Neither is it intended to defend the interpretation of any of the data from these tests. After all, it is the interpretation of the data which is really attacked for the value of the field experiments lies mainly in the conclusions which are drawn from the results secured. When the first shock from the very startling statement given above has passed, the reaction which it brings about will undoubtedly be of distinct value from the standpoint of improving soil experiments. In other words, extreme views and statements frequently accomplish much good even if they are found to be too radical, for they stimu-

late study, thought and investigation, and in this case the sweeping condemnation of all field experiments will certainly cause more care to be taken in planning and carrying them out and in interpreting the data.

The field experiments of the past need no defense, they need study and the conclusions drawn from them should be utilized in present day work. Without question there have been weaknesses in the plan of experiments, faults which could not be foreseen, difficulties which could not be overcome, and conclusions have been drawn which were not entirely warranted. But assume all this to be true and the method of field experimentation still remains fundamentally sound. If it needs improvements, those improvements will come as a result of study. The Agronomy Society has a special committee collecting and tabulating all available information regarding field experiments and eventually the Society will adopt certain definite standards for such work. This will be a long step in advance and will make field experiments more valuable. The development of the soil survey work has yielded information regarding soil types which is bringing about desirable changes in the matter of locating experiment fields. Probably no other factor has been so completely overlooked, in the locating of fields as the selection of an area where the soil is of a definite type. In most cases expediency or nearness to the Experiment Station or a similar reason has controlled the selection of a field but the tendency now is to consider the soil type first and other considerations follow logically. Much more might be said along this line and other ways in which field experiments could be improved might be suggested but such a discussion is left for a later date when the recommendations of the Agronomy Society committee come up for final action.

It has been assumed that practically all will agree that the arraignment of field experiments is unwarranted and that there is no immediate likelihood of their discontinuance. Hence no defense of the principle of field experiments seems needed, other than the few comments which have been offered. The question of making such tests of the largest possible value is one however, which continually presses for attention.

IOWA EXPERIMENTS

A thorough study of the whole subject of soil experiment fields and their value was made when the Iowa Experiment Station began the rather extensive tests now under way. An attempt was made to profit by the experiences of the past, to modify plans to fit local conditions, and to get away as far as possible, from the objectionable features of the older fields. Just how the experimental data will be interpreted, what the outcome of the work in general will be, cannot now be predicted. Some results secured at the present time however, may be cited to indicate the effects of certain fertilizers on individual soil types under general farming conditions, and a comparison of the results from various fields will show the effects of the soil type on the results, the seasonal effects are shown in the results in different years and the

general value of these field experiments to Iowa farmers may be apparent from the nature of the results.

The general plan which has been followed in the Iowa soil experimental fields has been to locate a series of plots in various parts of the state on individual soil types. These fields have been laid out following the survey of a county and the location has been very carefully selected, every precaution

TABLE 1

The effect of applications of manure on crop yields on individual soil types in Iowa

EXPERIMENT FIELD	COUNTY	SOIL TYPE	CROP	YEAR	YIELD ON CHECK PLOT	YIELD ON MANURE PLOT
					bu. or tons	*bu. or tons*
Waverly No. 2	Bremer	Carrington loam	Corn	1918	38.5	54.0
Waverly No. 2	Bremer	Carrington loam	Oats	1919	39.8	49.3
Clarinda	Page	Marshall silt loam	Corn	1920	54.3	64.4
Agency	Wapello	Grundy silt loam	Oats	1919	44.9	62.2
Agency	Wapello	Grundy silt loam	Wheat	1920	22.7	31.5
Everly	Clay	O'Neill loam	Clover	1921	1.80	2.35
Eldridge	Scott	Muscatine silt loam	Corn	1918	66.6	74.4
Eldridge	Scott	Muscatine silt loam	Oats	1919	43.2	50.7
Eldridge	Scott	Muscatine silt loam	Corn	1921	62.1	72.1
Eldora	Hardin	Carrington loam	Corn	1919	33.9	52.5
Eldora	Hardin	Carrington loam	Oats	1920	42.8	49.6
Jesup	Blackhawk	Carrington loam	Clover	1919	1.17	2.08
Jesup	Blackhawk	Carrington loam	Corn	1921	58.7	72.8
New London	Henry	Grundy silt loam	Clover	1916	2.10	2.90
New London	Henry	Grundy silt loam	Corn	1917	49.4	61.7
New London	Henry	Grundy silt loam	Oats	1920	32.0	49.8
Spencer No. 1	Clay	Carrington loam	Corn	1918	30.4	46.9
Spencer No. 1	Clay	Carrington loam	Oats	1919	39.9	51.0
Spencer No. 1	Clay	Carrington loam	Corn	1920	37.6	46.9
Storm Lake	Buena Vista	Webster silty clay loam	Corn	1920	48.2	57.3
Truesdale	Buena Vista	Carrington loam	Corn	1920	47.5	57.0
Truesdale	Buena Vista	Carrington loam	Corn	1921	32.8	39.7
Blue Grass	Scott	Muscatine silt loam	Clover	1920	1.57	1.92
Calamus	Clinton	Carrington silt loam	Clover	1918	1.45	3.04
Calamus	Clinton	Carrington silt loam	Corn	1920	57.5	65.2
Hudson	Blackhawk	Muscatine silt loam	Oats	1919	47.6	54.7
Hudson	Blackhawk	Muscatine silt loam	Corn	1920	53.2	62.8
Osage	Mitchell	Carrington silt loam	Oats	1920	34.6	60.3
Sherfey	Muscatine	Clinton silt loam	Corn	1919	53.5	74.8

being taken that the soil be true to type, that it be true to typical topography of the type, that its past history be such that there be no interference from such factors as fence rows, manure piles, straw stacks, etc. Not only are the soil conditions very carefully selected but the cooperator is also carefully chosen. The aim is to secure an owner preferably and a man who is interested, willing to cooperate, and permanently located as far as can be determined.

The fields are located where a definite rotation is being practiced, whatever that rotation may be. The cooperator may be a livestock farmer or a grain farmer. In most instances the series of plots is so arranged that the tests include both types of farming and the results which are secured may yield valuable practical information regarding the relative merits of the two types of farming.

TABLE 2

The effect of lime on crop yields on individual soil types in Iowa

EXPERIMENT FIELD	COUNTY	SOIL TYPE	CROP	YEAR	YIELD ON MANURE PLOT	YIELD ON MANURE LIME PLOT
					bu. or tons	*bu. or tons*
Clarinda	Page	Marshall silt loam	Oats	1916	54.4	63.3
Clarinda	Page	Marshall silt loam	Clover	1917	1.36	1.56
Clarinda	Page	Marshall silt loam	Corn	1919	58.7	62.6
Clarinda	Page	Marshall silt loam	Oats	1920	52.3	61.8
Spencer No. 1	Clay	Carrington loam	Corn	1918	46.9	52.0
Spencer No. 1	Clay	Carrington loam	Oats	1919	51.0	59.7
Spencer No. 1	Clay	Carrington loam	Corn	1920	46.9	55.7
Alburnett	Linn	Clyde silt loam	Corn	1920	41.0	51.8
Alburnett	Linn	Clyde silt loam	Oats	1921	36.6	43.3
Blue Grass	Scott	Muscatine silt loam	Clover	1920	1.92	2.37
Blue Grass	Scott	Muscatine silt loam	Corn	1921	57.8	66.1
Waverly	Bremer	Carrington loam	Oats	1919	49.3	61.9
Waverly	Bremer	Carrington loam	Clover	1920	0.67	1.36
Mt. Pleasant 1	Henry	Grundy silt loam	Corn	1920	57.0	76.6
Mt. Pleasant 2	Henry	Grundy silt loam	Clover	1918	3.82	5.30
Mt. Pleasant 2	Henry	Grundy silt loam	Corn	1919	66.3	74.1
Mt. Pleasant 2	Henry	Grundy silt loam	Corn	1920	74.9	82.2
Sawyer	Lee	Grundy silt loam	Clover	1919	1.75	2.10
Sawyer	Lee	Grundy silt loam	Timothy	1920	3.48	4.17
West Point 1	Lee	Grundy silt loam	Oats	1919	41.5	43.5
West Point 1	Lee	Grundy silt loam	Clover	1920	1.87	2.89
Farson	Wapello	Grundy silt loam	Clover	1920	1.19	1.43
West Point 2	Lee	Grundy silt loam	Clover	1919	1.59	1.87
Eldridge	Scott	Muscatine silt loam	Corn	1918	74.4	81.8
Eldridge	Scott	Muscatine silt loam	Oats	1919	50.7	64.3
Low Moor	Clinton	Carrington silt loam	Timothy	1920	2.13	2.77

All the usual precautions are taken in locating the fields with regard to drainage, previous treatment of the soil, character of the crops grown and general method of farming practiced.

From preliminary studies it was determined that the soil problems of the greatest value in Iowa include the use of farm manure, the application of lime, the addition of phosphorus, either in the rock phosphate or acid phosphate form, the use of complete commercial fertilizers, and the turning under of crop residues. Hence the experimental fields have been planned to consist of 13 plots, part of which represent the livestock system of farming and test the use of manure with lime, phosphorus carriers and a complete fertilizer.

TABLE 3

The effect of phosphorus on crop yields on individual soil types in Iowa

EXPERIMENT FIELD	COUNTY	SOIL TYPE	CROP	YEAR	YIELD ON MANURE LIME PLOT	YIELD ON MANURE LIME ROCK PHOSPHATE PLOT	YIELD ON MANURE LIME ACID PHOSPHATE PLOT	YIELD ON MANURE LIME COMMERCIAL FERTILIZER PLOT
					bu. or tons	*bu. or tons*	*bu. or tons*	*bu. or tons*
Clarinda 1	Page	Marshall silt loam	Oats	1917	88.0	91.0	103.6	98.0
Clarinda 1	Page	Marshall silt loam	Clover	1918	1.20	1.75	1.50	1.70
Clarinda 1	Page	Marshall silt loam	Corn	1919	57.3	60.9	64.5	61.5
Newell	Buena Vista	Webster silty clay loam	Corn	1919	54.4	61.4	65.1	70.9
Newell	Buena Vista	Webster silty clay loam	Oats	1920	63.5	69.7	76.3	68.9
Orange City	Sioux	Marshall silt loam	Corn	1919	80.8	86.1	90.6	88.5
Orange City	Sioux	Marshall silt loam	Corn	1920	54.9	58.2	58.2	56.0
Storm Lake	Buena Vista	Webster silty clay loam	Corn	1920	58.1	64.2	76.5	80.0
Alburnett	Linn	Clyde silt loam	Corn	1920	51.8	61.5	63.0	83.3
Blue Grass 2	Scott	Muscatine silt loam	Clover	1919	2.94	3.06	3.06	3.16
Calamus	Clinton	Carrington silt loam	Clover	1918	3.38	4.39	5.18	4.35
Calamus	Clinton	Carrington silt loam	Clover	1919	0.74	1.22	2.11	1.66
Delmar	Clinton	Muscatine silt loam	Barley	1920	24.9	32.7	32.7	40.3
Eldora	Hardin	Carrington loam	Clover	1918	1.27	2.87	2.56	1.88
Eldora	Hardin	Carrington loam	Corn	1919	51.8	53.6	57.2	51.7
Hudson	Blackhawk	Muscatine silt loam	Corn	1920	67.4	73.3	73.3	72.4
Jesup	Blackhawk	Carrington loam	Corn	1918	40.4	52.7	50.3	59.2
Jesup	Blackhawk	Carrington loam	Oats	1919	40.5	43.5	52.4	58.9
Jesup	Blackhawk	Carrington loam	Clover	1920	1.10	1.57	2.20	2.00
Jesup 2	Blackhawk	Carrington loam	Clover	1919	1.86	1.92	2.22	2.80
Letts	Muscatine	Muscatine silt loam	Corn	1918	77.2	82.9	83.7	84.8
Letts	Muscatine	Muscatine silt loam	Oats	1919	58.6	62.6	62.6	67.4
Letts	Muscatine	Muscatine silt loam	Wheat	1920	23.9	28.5	27.5	31.2
Mount Joy	Scott	Muscatine silt loam	Alfalfa	1919	2.52	3.20	2.96	3.12
Waverly	Bremer	Carrington loam	Clover	1919	2.02	2.10	3.10	2.84
Waverly	Bremer	Carrington loam	Corn	1920	87.8	94.0	101.5	94.2
Mt. Pleasant	Henry	Grundy silt loam	Clover	1919	3.99	4.98	6.47	6.93
Mt. Pleasant	Henry	Grundy silt loam	Corn	1920	82.2	88.6	101.4	88.4
Rome	Henry	Clinton silt loam	Timothy	1920	0.95	1.63	2.85	1.63

The other portion of the series tests the use of crop residues instead of manure with the same fertilizers applied, this latter portion representing the grain system of farming.

There are some variations being made in new fields which have been established and in several of these additions of potassium are being made. With a few exceptions the field experiments of the state have been under way for a period of only five years and thus far yields have been secured for four seasons. Experience with field experiments teaches that data must be secured over a period of years before it should be interpreted, in order to take care of factors which unavoidably interfere with the results in individual years. Hence it is, of course, too early to draw definite conclusions from most of the Iowa fields. The data, however, is proving of considerable interest and value at the present time and it is possible, in fact, to draw from the results already secured certain conclusions of practical value to farmers. Some of the data secured during the past few years is included here in order to illustrate the results which are being secured from the use of the various fertilizing materials on individual soil types. These figures have been compiled to show separately the effects of manure, of lime, and of phosphorus fertilizers and are given in tables 1, 2 and 3. It is not intended to consider these tables in detail but merely to call attention to the practical conclusions to which they may lead, and to emphasize the significance of the results of such tests as planned and carried out in Iowa from the standpoint of increased crop production and permanent soil fertility.

It is always, desirable, of course to calculate all results on an economic basis and this method will be followed in future interpretation of the Iowa data. At present, however, it is felt that the data is not sufficiently complete to warrant such economic interpretation. In a few instances where calculations have been made, it has been shown that certain fertilizing materials increase the yield of certain crops on many individual soil types to a profitable extent. There is no reason to doubt but that the results secured in these experiments during the next few years will prove of large value to Iowa farmers and to the agriculture of the state.

In conclusion it should be emphasized that too much care cannot be taken in planning and laying out field experiments. Some must unavoidably be relinquished—occasionally accidents will happen in making applications or securing results, but the data secured from such field tests over a period of years provides the only definite practical economic solution of the soil fertility problem of the individual farmer.

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SOME WAYS OF INCREASING THE DUTY OF IRRIGATION WATER

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Duty of water is perhaps the broadest problem with which the irrigationists have to deal. Duty-of-water data is of value to water boards and courts in determining water rights, to engineers in fixing capacities of canals and reservoirs, and to agriculturists in the control of soil moisture.

The amount of water needed for each of the chief soil classes and for each important group of crops varies according to their water requirement, average yields, and relative acreage on each project. Meadows constitute 52 per cent of the irrigated land on all government projects according to the crop census of the United States Reclamation Service. Meadow crops require about twice as much water as do annual crops, hence they deserve about 75 per cent of the consideration in fixing an average duty of water for a given area.

The amount of water provided affects the estimates and final cost, determines the area it is possible to irrigate, and has its effect upon the security of investment in irrigation and the ultimate agricultural and financial success of a project. To secure economical use of water on an irrigation project and avoid alkali and drainage problems there must be a good distribution system and each farmer must use water intelligently.

Too little water results in crop shortage, while excessive irrigation may lessen the crop and injure the soil in places to the point of unprofitable production. It is better economy to provide only a moderate allowance of water with reasonably priced structures than to provide a liberal supply at a greater expense and invite drainage assessments later on. The aim should be to get the highest practicable efficiency out of every acre-inch of rainfall and every supplementary inch of irrigation water provided. The cost of water that will give the greatest net profit an acre will generally represent the limit of preventable loss under present economic conditions.

A score of different factors affect the duty of water. Those affecting storage, conveyance and distribution losses and soil and crop requirements have been discussed in a previous paper (2). It is the purpose of this paper to present some additional data bearing on a few of the chief ways of increasing duty of water.

USABLE WATER CAPACITY OF SOILS

The field capacity of soils for storing usable soil-moisture affects the amount and frequency of irrigation and total quantity required per season very much. In duty-of-water studies it has often been found that farmers will apply six or eight inches of irrigation to a soil which has capacity to retain not over four inches. The surplus removes valuable plant foods, may cause drainage problems on adjacent low lands and involves needless expense.

Field water-capacity tests have been made in Oregon in connection with irrigation investigations for the leading soil types in the chief irrigated sec-

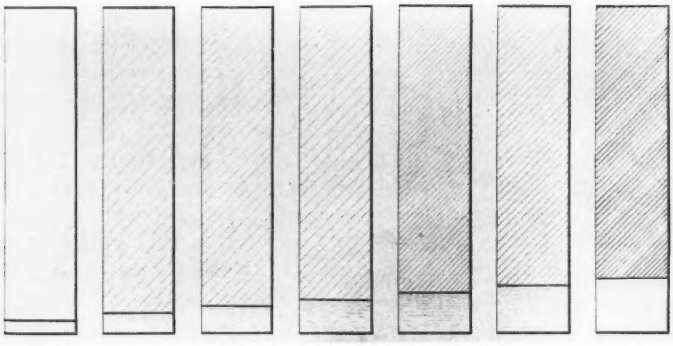

FIG. 1. USABLE WATER CAPACITY OF SOIL CLASSES

tions of the State. Duplicate tests are made using sheet metal cylinders 1 foot long and 6 inches in diameter. These are forced into the moist soil their entire length and are then dug out, struck off flush at the bottom and covered with a perforated base. These cores are then saturated, drained to constant weight in the covered jars, and their water retaining capacity determined by oven drying samples of the core. Other moisture points such as drought point and excess points are determined by methods described elsewhere (1). From these studies a generalized chart, figure 1, has been prepared as a guide to irrigators showing the usable water capacity of soil classes.

Modern irrigation contemplates that water be measured and applied in known quantities according to capacity of the soil and extent of the root system of the crop. Then to irrigate an acre of potatoes in which the feeding roots are largely within the first three feet of soil, on a fine sandy loam soil,

having usable water-capacity of one acre-inch to the foot, three acre-inches will be required, provided the soil is dried out to the drought point. Since a cubic foot per second will make an acre inch in an hour it will require three hours with such a flow to irrigate the patch. The writer has shown elsewhere (3) that the wilting point has an important bearing on the best time to irrigate to obtain highest yield and duty of water.

VALUE OF ROTATION AND MANURE

Rotation of crops costs little and is very profitable on all soils. It permits increasing the humus and nitrogen supply by the turning under of legume sod and manure and crop residues thus increasing the water capacity, tilth and fertility. A 3-year rotation at the Oregon Experiment Station has, in 9 years, averaged a yearly net profit under irrigation of $14.09, while rotation and manure under irrigated conditions has increased the net profit an acre

TABLE 1

Value of rotation—nine year average

TREATMENT	AVERAGE YEARLY YIELD		AVERAGE NET PROFIT			WATER REQUIREMENT PER POUND DRY MATTER
	Per acre	Per acre inch	Per acre	Grain from rotation or manure	Per acre inch	
	bu.	*bu.*				*lbs.*
Beans:						
Continuous unirrigated	9.24		$11.55			2909
Rotated unirrigated	10.13		20.37	$8.82		2249
Rotated and manured unirrigated	12.91		21.26	9.71		1900
Irrigated continuous	9.85	3.82	15.37		$5.12	2622
Irrigated and rotated	15.74	6.10	29.46	14.09	9.82	1794
Irrigated, rotated and manured	18.29	7.14	38.39	23.02	12.80	1425

from beans by $23.02. The detailed data are presented in table 1. The rotation used was grain, clover, and beans. The yield and net profit per acre-inch are about doubled by the rotation and manure. The water requirement per pound of dry matter is reduced by these treatments nearly one-half. This water requirement is determined by sampling the soil at time of emergence of the plants and again at harvest, determining the soil moisture of each sample, and adding to the difference in pounds per acre the pounds of rain and irrigation water. The dry matter in the crop at harvest time was also determined so that, water-duty might be exactly measured as the ratio of water consumed to dry crop produced.

CROP PRODUCING POWER OF WATER

The water requirement has been determined for about sixty crop-plots each year for the past dozen years in connection with duty-of-water trials at the

Oregon Station (2). By hand picking each year the plat of each crop which gave the maximum net profit an acre and calculating the average water requirement of the best paying plat by years the twelve year average water requirement for the most profitable irrigation with good modern methods of farming has been obtained. This figure is given in average inches for different crops in figure 2.

It has taken 5.23 acre-inches to make a ton of dry alfalfa under good conditions as a twelve year average. This represents the net duty of water for this crop. That is, the duty of water is not likely to be less than fifteen to

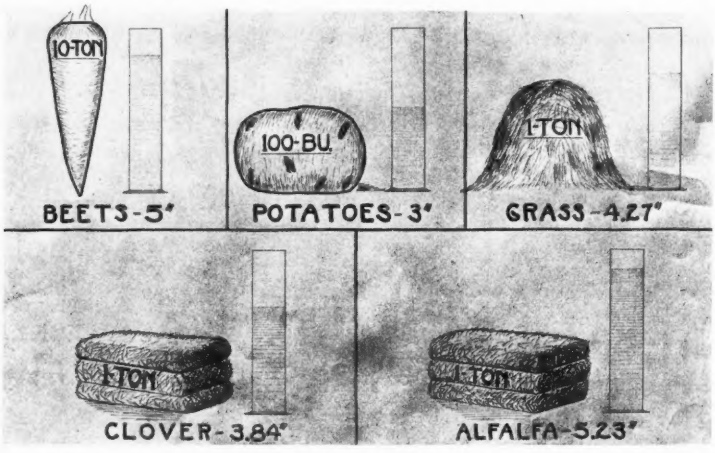

FIG. 2. WATER REQUIREMENT OF CROPS ON PLOTS RETURNING MAXIMUM NET PROFIT EACH YEAR, BASED ON A 12-YEAR AVERAGE

eighteen inches in a three-ton country or thirty to thirty-six inches in a section capable of producing 6 tons an acre a year.

Potatoes, similarly, are not likely to be produced with less than three acre-inches per hundred bushels.

RELATION OF FERTILITY TO WATER REQUIREMENT

As indicated in the last column of table 1 the fertility of the soil affects the amount of water required per pound or per ton of dry crop produced. This was recognized and reported by the writer as early as 1912 and has been noted by others (1). Desiring more exact data on the matter a tank experiment was arranged to determine the water requirement of oats grown on two soils with different fertilizer treatments. One soil of strong fertility gave moderate variations in water cost with the different treatments, the other a soil of medium fertility, gave a striking difference in yield and water requirement (table 2). Other data published and unpublished from the Oregon Station substantiates the importance of fertility as affecting water requirement and

duty of water. The richer and better balanced nutrient solution gives a lower water requirement.

The irrigation requirement and water requirement will vary somewhat with the season and anything which affects the evaporation, percolation or transpiration of soil moisture. Anything that contributes to good irrigation-farming such as planting, irrigating or cultivating at the right time, tends toward economical use of irrigation water. Proper economical irrigation is

TABLE 2

Relation of fertility to water requirement

Oats on Deschutes medium sandy loam soil

TREATMENT		Yield	WATER REQUIREMENT PER POUND OF DRY MATTER
Fertilizer	Amount per acre		
	lbs.	*gm.*	*lbs.*
Untreated	0	16.2	2125
Sulfur	100	57.9	594
Potassium chloride	160	37.5	1020
Tri-calcium phosphate	100	35.9	1034
Sodium nitrate	100	44.8	842
Sulfur	100	42.3	867
Sodium nitrate	100		
Sulfur	100	40.7	946
Potassium chloride	160		
Sulfur	100	29.2	1202
Tri-calcium phosphate	100		
Sodium nitrate	100	58.5	650
Potassium chloride	160		
Tri-calcium phosphate	100		
Untreated	0	15.0	2219
Manure	10 tons	76.3	390

necessary to permanent irrigation agriculture. It is fundamentally important in irrigation farming to practice a careful rotation of crops that will permit plowing in legume sod and crop residues every few years to keep up water capacity and fertility and lower the water requirement. If we can save 50 per cent of the water used in many places we can practically double the crop producing power of such areas. Furthering the economical use of water will, therefore, help to establish highest productive values and add permanently to the food output and wealth producing area.

The problem of economic duty of water is admittedly complex, but all the agricultural wealth developed and undeveloped in the arid West will be favorably affected by its proper determination. The cost of investigations would be returned many fold by security gained from water litigation.

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A STUDY OF THE CAUSES OF FROST OCCURRENCE IN MUCK SOILS

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INTRODUCTION

It is a very general observation that when a rather light frost occurs during the growing season, frost-susceptible plants growing on muck and peat lands are almost invariably injured, while the same plants growing on mineral soils, adjacent to and on the same level as the muck and peat lands, are generally not touched. Our observations and investigations for a period of years with corn and certain truck crops have confirmed this general belief. Very often the boundary line between the organic and mineral soils is distinctly shown by the line of frozen plants. It has even been observed that where the muck or peat has been burned the plants grown on it escaped a frost while those on the unburned peat and muck were killed.

Up to the present time there appears to be no definite and satisfactory explanation for the phenomenon; various notions and hypotheses exist, but there seems to be no experimentally proved explanation. A true and definite explanation of the phenomenon is of the greatest practical importance, since the large areas of muck and peat lands in the United States constitute so important a portion of the crop-producing land of the country.

The Soils Department of the Michigan Agricultural Experiment Station inaugurated in 1911 a study of the soil temperature. Results of these investigations have already been reported (1, 2). In 1918 a study of the causes of frost occurrence in muck and peat lands was also commenced, and it is the purpose of this paper to present a preliminary and very brief report of a portion of the results obtained from this investigation thus far. At a later date it is hoped to present a detailed and complete report.

There are four principal factors which may be responsible for the difference in frost occurrence between organic and mineral soils. These are difference in color, difference in temperature of the air at various elevations, difference in specific heat by volume of soil, and difference in heat conductivity.

It is an accepted fact in physics that color has a very marked effect upon radiation as well as upon the absorption of heat. It is claimed that radiation and absorption are closely related, that the best absorbers are also the best radiators, and the poorest absorbers the poorest radiators. A black substance,

for instance, is able to absorb practically all the heat rays on account of its low reflection, low diffusive power and high absorptive power, is a good heat absorber and also a good heat radiator. The opposite is true of a white substance. A white substance on account of its high reflective, high diffusive power and low absorbing power, is a poor absorber and a poor radiator.

Some soil physicists have concluded, therefore, that the black soils attain a very high temperature during the sun insolation, but that their temperature during the night is about the same if not lower than that of the light-colored soils on account of greater radiation.

It has been shown (1), however, that color has no effect upon radiation in darkness. From a theoretical consideration it seems that it should not, because all colors emit in dark rays of low refrangibility which are the same, while all the rays they absorb from the sun are of high refrangibility and are different.

Color, therefore, is probably not the factor responsible for the difference of frost occurrence between organic and mineral soils.

Difference in air temperature due to elevation and air drainage cannot be considered as an operating factor since the plants observed in these studies were growing on mineral soils adjacent to and on exactly the same elevation as the muck and peat soils.

The third factor has to do with the specific heat of soils by volume. Under natural and field conditions we find that muck and peat, on account of their large water content, possess a much greater specific heat by volume than do the mineral soils. This would, however, favor the organic rather than the mineral soils in the prevention of frost. Specific heat by volume is, therefore, probably not the responsible factor.

The fourth factor is the difference in heat conductivity between the organic and mineral soils. It is a well-established fact, of course, that under field conditions peat and muck conduct heat at considerably lower rates than the mineral soils. The results presented in this paper indicate that this factor is probably responsible, at least under normal conditions, for the difference in frost occurrence on the organic and mineral soils.

PLAN OF INVESTIGATION

In order to study the influence of the factors just discussed, an investigation was arranged and prepared as follows:

On a low and level bottom land consisting wholly of muck and peat several feet deep, a pit about 8 feet square and 6 feet deep was dug. On a neighboring hill, only about 200 feet distant but about 40 feet higher in elevation, a similar pit was dug. The soil of this hill consisted of clay loam. The pit on the muck land was filled with the silty clay from the hill and the pit on the hill was filled in turn with the muck soil from the muck land. In both cases the soils were thoroughly and carefully compacted and considerable time was allowed for them to settle before the experiment was commenced. Close to the pit containing the mineral soil a small tract of muck land was divided into three strips and treated differently.

The soil in one strip was maintained compact, in the second cultivated and in the third compact and covered with a thin layer of sand. Likewise, close to the muck pit on the hill, a strip of the native soil was kept compact and free of vegetation.

The temperature of the soils was measured directly at the surface, about 1 inch above the surface and at 6 inches below the surface. Air temperatures were taken at about 1 inch and at 6 feet above the soil surface.

Standard minimum thermometers were employed for the measurement of the temperature of the air and of the surface soil, while special mercury thermometers were used for the temperature of the soil at lower depths.

It is well recognized, of course, that it is not easy to determine the temperature of a gas, because the thermometer does not indicate the temperature of the surrounding medium, but the temperature of its own bulb. If a thermometer is surrounded by an opaque fluid or solid, it takes up heat by conduction from the surrounding medium and thus indicates the temperature of that medium. If the bulb of a thermometer is exposed in a gas, however, its temperature is determined both by the conduction of heat to or from the surrounding medium and the differences between the radiant energy absorbed and emitted by the thermometer.

In order to measure, as closely as possible, the real temperature both of the air and of the surface soil, each thermometer used for measuring the air temperature was housed in a shelter exactly like those used by the United States Weather Bureau. It consisted of a rectangular box about 20 inches long, 20 inches high and 10 inches wide, with a sloping roof, closed bottom and latticed sides. This box, with the thermometer inside, was placed right on the surface of the ground or at a height of 6 feet.

The thermometers for measuring the surface soil temperature were placed on the surface and their bulbs were covered with a very thin layer of soil.

For measuring the influence of the soil temperature on that of the air immediately above the soil, two procedures were followed. One consisted of placing the minimum thermometer about one inch above the surface soil and leaving the bulb entirely unprotected and exposed. The second consisted of protecting or screening the thermometer by placing it in one of the boxes described above from which the bottom had been removed. The temperature inside of the box, then, was influenced by the temperature of the soil. At the same time, however, the box served to screen or protect the thermometer against direct radiation into space.

EXPERIMENTAL RESULTS

Experimental results and field observations have been gathered for the last three years upon the subject, but since it is intended to publish these data in a rather detailed report later, only a few typical results will be presented here at present.

In table 1 are shown the temperature records of the whole experiment as described, for the night of October 5, 1921. This was the first night that frost occurred in the fall of 1921 for this region. Table 2 shows the temperature of the soils during the day preceding.

An examination of the results in table 1 reveals some most interesting and remarkable differences in temperature in the various soils and in the air. In the first place, they show that the temperature of the air varies greatly with the elevation.

In the second place, the data show that the clay loam had the highest surface minimum temperature, followed by sand-covered muck, compact muck and cultivated muck, in order. The surface temperature of the clay loam at the bottom land was 36.2°F., that of the sand-covered muck 31.8°, compact

TABLE 1

*Minimum temperature of air and soils for the night of October 5, 1921**

POINT OF MEASUREMENT		TEMPERATURE	
		On bottom land	On hill
		°F.	°F.
Air	6 feet above ground	32.0	35.0
	1 inch above surface	29.0	33.5
Clay loam compact	On surface	36.2	35.5
	1 inch above surface (thermometers in box)	34.2	35.0
	6 inches deep	46.5	47.0
Muck compact	On surface	31.0	32.0
	1 inch above surface (thermometers in box)	31.8	34.5
	6 inches deep	50.5	52.1
Muck cultivated	On surface	28.0	
	1 inch above surface (thermometers in box)	30.5	
	6 inches deep	51.4	
Muck, compact and covered with layer of sand	On surface	31.8	
	1 inch above surface (thermometers inb ox)	32.8	
	6 inches deep	49.8	

* These results represent single determinations but they are typical of a great number of measurements made during four years.

TABLE 2

Maximum temperature of soils at 1 and 4 P.M. during the day of October 5.

POINT OF MEASUREMENT		BOTTOM-LAND TEMPERATURE		HILL TEMPERATURE	
		1 p.m.	4 p.m.	1 p.m.	4 p.m.
		°F.	°F.	°F.	°F.
Clay loam compact	On surface	55.0	57.0	56.0	58.0
	6 inches depth	54.1	54.0	54.0	54.8
Muck compact	On surface	58.0	57.0	57.0	58.0
	6 inches depth	51.2	53.1	52.7	54.0
Muck cultivated	On surface	57.0	57.0		
	6 inches depth	51.7	53.2		
Muck, compact and covered with layer of sand.	On surface	56.0	58.0		
	6 inches depth	51.8	54.0		

muck 31, and cultivated muck 28. The difference in temperature between the clay loam and the cultivated muck is 8.2°.

The same variation in temperature exists between the clay loam and the muck on the top of the hill. The temperature of the muck at this place is 32°, that of the clay loam 35.5°, or a difference of 3.5° in favor of the latter.

Now it is to be noted that while the temperature of the clay loam is higher than that of the muck at the surface, at the 6-inches depth it is the muck that has the higher temperature. It will be seen that when the minimum temperature was attained at the surface the temperature of the cultivated muck at the 6-inches depth is 4.9° and that of the compact muck 4° higher than that of the clay loam. Yet at the surface the temperature of the clay is 8.2° higher than that of the cultivated muck.

This difference cannot be due to any accumulated difference in the temperature between the various soils during the day, because the records in table 2 show that the temperature of all the soils at the various depths during the preceding day is about the same. Thus, at about 4 o'clock in the afternoon the temperature of the various soils at the corresponding depths is about equal.

The most apparent and logical explanation for the difference in temperature at the surface between the mineral and organic soils and consequently for the difference in frost occurrence between them, seems to lie in the difference of their heat-conducting power. The mineral soils are good conductors of heatl while the organic soils are comparatively poor conductors of heat. The mineral soils, therefore, allow the heat, which has been accumulated at the various depth, during the day, to travel to the surface at a greater speed than in the case of the organic soils. The result is that the surface of the mineral soil is kept at a higher temperature, while that of the organic soils is allowed to become excessively cold, even though their temperature at the lower depths is much higher than that of the mineral soils. The air above the mineral soils, therefore, is warmed to a correspondingly greater degree than that above the organic soils, and in a night when not too heavy a frost occurs, the mineral soils are able to prevent a frost, while on the organic soils frost occurs.

The effective influence of the soil-surface temperature on the air temperature above is strikingly illustrated by the results in table 1. It will be seen that the temperature of the air one inch above the clay is 34.2°F., while that above the cultivated muck 30.5°, or a difference of 3.7°.

This influence is further remarkably illustrated under actual field conditions. It has been abundantly observed that when a heavy frost occurs in the soil so that even the plants grown on the mineral soils are bitten by it, in the case of corn only the top portion is frozen, the lower portion, which is nearer to the influence of the surface-soil temperature is not at all touched, while the corn grown in the adjacent muck land is frozen from top to bottom.

It is to be further noted from table 1 that not only is the surface temperature of the muck lower than that of the mineral soil, but it is even lower than that of

the air one inch above. Thus, the surface temperature of the cultivated muck is 28°F., while that of the air one inch above is 30.5°. On top of the hill it is 32° for the muck and 33.5° for the air. In the one case the surface of the mineral soil, however, is 2° warmer than the air one inch above.

The factor of heat conductivity, therefore, appears to be mainly responsible for the difference in frost occurrence on these soils. The agents or cultural practices that tended to accelerate the heat-conducting power of the soil, tended also to minimize the danger of frost occurrence. Packing of the soil and especially of the organic soils, and a high moisture content both help to increase the rate of heat transference of soils.

The influence of packing is very strikingly shown in table 1, where it is seen that the temperature of the compact muck at the surface is 31°F., while that of the cultivated is 28°, or a difference of 3° in favor of the compaction.

The influence of the water-content is well exemplified by the following practical observation. In the fall of 1920, corn grown in a basin of muck land where the drainage was very poor and the water-table and moisture-content high, was hardly touched by a frost, while the corn grown on the surrounding muck land with a slightly higher elevation and much drier, was completely killed by the frost. Professor Alway has related to us somewhat similar observations in Minnesota.

Referring once more to table 1, it will be seen that the surface temperature of the muck covered with a thin layer of sand is slightly higher than that of the compact muck. The cause for this difference is not altogether clear, but, probably it is due to some way in which the layer of sand favorably affects the heat conductivity of the muck. It may accomplish this by acting as a mulch and thereby maintaining a higher moisture content and by forming a more compact layer of soil at the surface.

The striking effect of the sand mulch on the temperature of the muck is further confirmed in a four years temperature measurement of gravel, sand, loam, clay and muck (2). These data show that when the muck was covered with a thin layer of sand its average temperature during the summer months was appreciably higher both at the 2- and the 12-inch depth than that of all the mineral soils. When not covered with the sand layer its average temperature was somewhat lower than that of the mineral soils. The higher average temperature in the former case was explained on the basis that the sand layer, acting as a mulch, diminished the water evaporation and the heat which would otherwise be expended in the evaporation of the water went to warm up the soil mass itself.

Another soil factor which appears to have an appreciable bearing on freezing of plants is the soil fertility. Various observations show that where soils have been rather heavily fertilized, corn or truck crops grown on them may sometimes escape a frost, while the same kind of plants grown on adjacent soil, but unfertilized, may be completely killed by the frost.

SUMMARY

The present paper is a preliminary report of an investigation on the causes of frost occurrence in muck soils. It is a general observation that when a frost occurs during the growing season, plants grown on muck and peat soils may be completely killed by the frost, while the same plants grown on mineral soils adjacent to and even on the same level, may not be at all touched by the frost.

Results obtained seem to show that heat conductivity is the predominant factor responsible for this difference in frost occurrence. The mineral soils are good conductors of heat, while the organic soils are comparatively poor conductors of heat. The mineral soils, therefore, allow the heat, which has been accumulated at various depths during the day, to travel to the surface at a greater speed than in the case of the organic soils. The result is that the surface of the mineral soils is kept at a higher temperature, while that of the organic soils is allowed to become excessively cold, even though their temperature at the lower depths is much higher than that of the mineral soils. The air above the mineral soils, therefore, is warmed at a correspondingly greater degree than that above the organic soils, and on a night when not too heavy a frost occurs the mineral soils are able to prevent a frost, while on the organic soils frost occurs.

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THE RELATION OF SOIL MOISTURE TO PHYSIOLOGICAL SALT BALANCE FOR PLANTS[1]

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INTRODUCTION

This paper deals primarily with soil moisture in relation to the physiological balance of the mineral elements required for plant growth. It presents the results of an experimental study of the growth of young buckwheat plants in soil cultures and corresponds to a somewhat similar investigation described in a previous publication (10) dealing with the growth of young wheat plants in sand cultures to which nutrient solutions were added in such a way as to produce different degrees of moisture in the cultures of the three different series employed.

As explained in the earlier paper, the purpose of these investigations was to determine in what manner the physiological balance of salt proportions (as these affect the growth of plants) is influenced by different moisture conditions of the substrata in which the plants are grown, and further to study the effectiveness, or the relative plant-producing value, of various combinations of the active fertilizer elements under different soil moisture conditions.

PLAN OF THE EXPERIMENTS

Buckwheat was grown in soil cultures for periods of four weeks. The soil used consisted of a homogeneous mixture of equal parts, by volume, of rich sandy loam and carefully washed, white, seashore sand. The soil was thus diluted with the sand in order that the mineral elements present in the medium might not too greatly obscure the effects of added salts upon the growth rates of the plants. The maximum water-retaining capacity of this mixture, determined according to the method of Hilgard (5) was 31.24 per cent on the dry-weight basis, this value being the average of five determinations. To the soil cultures prepared with the above described mixture the fertilizer salts were added in the form of solutions each of which contained the three salts, KH_2PO_4, $Ca(NO_3)_2$, and $MgSO_4$. The solutions used comprised a series of 21 different sets of salt proportions and are described as the solutions of type I in a "plan for cooperative research prepared for a special committee of the National Research Council," (6) but as here used the solutions had higher total concentration values than that specified in this plan.

The solutions were added to the air-dry soil in such quantities as to produce the same initial moisture conditions in all the cultures of a single series. Corresponding cultures of the various series were all alike with respect to the proportions of the salts added to the soil but

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differed from each other in the soil-moisture content. All the soil cultures of one series were prepared to have 30 per cent moisture based on the maximum water-retaining capacity of the soil, the cultures of a second series had a moisture-content of 60 per cent, and those of a third series had a moisture-content of 80 per cent on the same basis. The initial moisture-content of the cultures of the second series was chosen to approximate that required for optimum growth of the plants, while that of the cultures of the first and third series, respectively, was considerably above and below this optimum. All the fertilizer elements added to the soil were supplied in this initial application of the solutions to produce the required moisture-content of the soil cultures which was subsequently maintained by the frequent addition of distilled water to each culture in sufficient quantities to restore the moisture lost through transpiration. Evaporation from the surface of the soil was prevented by a wax seal (2).

In creating the required initial soil moisture-content of corresponding cultures of the three series, as was here done by the use of nutrient solutions, it was not possible of course, to prevent the introduction of variable factors other than that of soil moisture and these must be considered in relation to the growth of the plants. The variable factors in question are those of total salts added per culture, total salts per unit volume of soil (involving total concentration of the soil solution), and the amounts of soil used per culture which depend upon the three possible methods of creating the required initial moisture conditions of the soil cultures by the use of nutrient solutions. These three methods were used in the present work which gave rise, unavoidably, to as many sets of experimental possibilities, each involving the three series of soil cultures above described.

The experimental possibilities, representing the unavoidable sets of cultural differences to which the plants may be subjected, with the given differences in the initial soil-moisture content in corresponding cultures of the three series, are set forth in table 1. The table is divided into three horizontal sections each of which give the data for a single group of cultures comprising the three series and representing one of the three sets of experimental possibilities. For the sake of convenience the groups are numbered consecutively I, II, and III and the series of each group will be designated the sub-optimal, optimal, and supra-optimal series according as the moisture-content of the cultures in the series was 30 per cent, 60 per cent, or 80 per cent of the maximum water-retaining capacity of the soil, respectively. The weights, in grams, of the air-dry soil used per culture, the amounts of solution in cubic centimeters added to the cultures of the different series to give the required moisture content, and the approximate total concentration values of the solutions, in atmospheres, are given. In the last two columns of the table are given the total salts per culture and the total salts per unit-volume of soil in terms of these values for the cultures of the optimal series taken as 1.00 in each case.

The methods used in creating the required initial soil-moisture and the soil conditions, with respect to other variable factors, resulting therefrom are briefly stated as follows: (1) Solutions alike in every respect were added in equal volumes to such amounts of soil as were inversely proportional to the required initial soil-moisture in corresponding cultures of the three series. The total salts per culture were then the same throughout and the total salts per unit volume of soil were directly proportional to the required soil-moisture in corresponding cultures. (2) Solutions alike in ever respect were added to equal amounts of soil in such volumes as were directly proportional to the required soil-moisture. The total salts per culture and the total salts per unit volume of soil were then also directly proportional to the required soil-moisture in corresponding cultures of the three series. (3) Solutions with total salt concentrations which were inversely proportional to the required soil-moisture, but alike in every other respect, were added to equal amounts of soil in such volumes as were directly proportional to the required soil-moisture. The total salts per culture as well as the total salts per unit volume of soil were then equal, respectively, in corresponding cultures of the three series. It is here assumed that the addition of the salts in the solution form to the soil of the various cultures was essentially the same in effect as adding the salts in the dry form to the soil and subsequently creating the required soil-moisture content by the addition of distilled water in the proper amounts.

The volume-molecular partial concentrations, which indicate also the molecular salt proportions of the 21 different solutions in each series of the three groups are given in table 2. The solution numbers refer to the positions which the solutions occupy in the triangular diagram representing the series as described in a "plan for cooperative research prepared for a special committee of the National Research Council," above cited.

In order to make the study as complete as possible the three groups of cultures as outlined in table 1, each group comprising the three series. were conducted simultaneously. Each series included in addition to the 21 treated cultures two check cultures which were prepared by adding distilled water instead of solutions to the air-dry soil in the proper amounts to produce the required initial soil moisture. It will be observed from the data of table 1 that all the optimal series were alike in every respect. These were, therefore, omitted from two of

TABLE 1

Numerical data describing the initial treatment and condition of the soil cultures employed in groups I, II and III

SERIES	AMOUNT OF SOIL USED PER CULTURE	SOIL-MOISTURE BASED ON MAXIMUM WATER-HOLDING CAPACITY	TOTAL AMOUNT OF SOLUTION ADDED TO EACH CULTURE	APPROXIMATE CONCENTRATION OF SOLUTIONS ADDED TO CULTURES	RELATIVE VALUES BASED ON THOSE OF OPTIMAL SERIES TAKEN AS 1.00	
					Total salts per culture	Total salts per unit volume of soil
	gm.	*per cent*	*cc.*	*atmospheres*		
Group I:						
Suboptimal	3200	30	300	1.75	1.00	0.50
Optimal	1600	60	300	1.75	1.00	1.00
Supra-optimal	1200	80	300	1.75	1.00	1.33
Group II:						
Sub-optimal	1600	30	150	1.75	0.50	0.50
Optimal	1600	60	300	1.75	1.00	1.00
Supra-optimal	1600	80	400	1.75	1.33	1.33
Group III:						
Sub-optimal	1600	30	150	3.50	1.00	1.00
Optimal	1600	60	300	1.75	1.00	1.00
Supra-optimal	1600	80	400	1.31	1.00	1.00

the groups in the actual experimentation leaving a total of seven series which were conducted simultaneously.

Half-gallon glazed earthenware pots were used as culture-vessels except for the cultures of the sub-optimal series of group I which required larger pots and for those of the supra-optimal series of the same group for which somewhat smaller pots were used. The seedlings were carefully selected from a large number grown on germinating nets (9). Four seedlings were transplanted to each soil culture previously prepared. The cultures were then continued until all the plants were in full bloom which required a period of 28 days from the time of transplanting.

Throughout the growth period, excessive changes in the moisture-content of the soil through the loss of transpirational water were prevented by weighing the cultures daily and supplying sufficient amounts of distilled water at each weighing to restore the original

moisture-conditions. During the last two weeks of the growth period the cultures were weighed twice daily and the original moisture conditions restored, unless the atmospheric conditions of the greenhouse in which the cultures stood were such as to permit only very low rates of transpiration. Under such conditions distilled water was addded to the cultures only once daily. The maximum loss of water from any culture of the three groups during any

TABLE 2

Volume-molecular proportions of KH_2PO_4, $Ca(NO_3)_2$, and $MgSO_4$ in the solutions added to the soil cultures in the proper amounts to create a soil-moisture content of 30 per cent, 60 per cent, and 80 per cent of the maximum water-retaining capacity of the soil in the sub-optimal, optimal, and supra-optimal series, respectively, in the different groups

SOLUTION NUMBER	VOLUME-MOLECULAR PROPORTIONS								
	Solutions used with the sub-optimal, optimal and supra-optimal series of groups I and II, and with the optimal series of group III (Concentration 1.75 atm.)			Solutions used with the sub-optimal series of group III (Concentration 3.50 atm.)			Solutions used with supra-optimal series of group III (Concentration 1.31 atm.)		
	KH_2PO_4	$Ca(NO_3)_2$	$MgSO_4$	KH_2PO_4	$Ca(NO_3)_2$	$MgSO_4$	KH_2PO_4	$Ca(NO_3)_2$	$MgSO_4$
R_1S_1	0.0047	0.0047	0.0282	0.0094	0.0094	0.0564	0.0035	0.0035	0.0211
S_2	0.0044	0.0086	0.0215	0.0088	0.0127	0.0430	0.0033	0.0064	0.0161
S_3	0.0042	0.0124	0.0164	0.0084	0.0248	0.0328	0.0031	0.0093	0.0123
S_4	0.0039	0.0156	0.0117	0.0078	0.0312	0.0234	0.0029	0.0117	0.0088
S_5	0.0039	0.0189	0.0075	0.0078	0.0378	0.0150	0.0029	0.0142	0.0056
S_6	0.0035	0.0213	0.0035	0.0070	0.0426	0.0070	0.0026	0.0160	0.0026
R_2S_1	0.0093	0.0047	0.0281	0.0186	0.0094	0.0562	0.0069	0.0035	0.0173
S_2	0.0086	0.0086	0.0173	0.0172	0.0172	0.0346	0.0064	0.0064	0.0130
S_3	0.0082	0.0124	0.0124	0.0164	0.0248	0.0248	0.0062	0.0093	0.0093
S_4	0.0079	0.0158	0.0079	0.0158	0.0316	0.0158	0.0059	0.0118	0.0059
S_5	0.0072	0.0182	0.0037	0.0144	0.0364	0.0074	0.0054	0.0136	0.0028
R_3S_1	0.0133	0.0044	0.0177	0.0266	0.0088	0.0354	0.0100	0.0033	0.0132
S_2	0.0126	0.0084	0.0126	0.0252	0.0168	0.0252	0.0094	0.0063	0.0094
S_3	0.0119	0.0119	0.0079	0.0238	0.0238	0.0158	0.0089	0.0089	0.0059
S_4	0.0114	0.0151	0.0037	0.0228	0.0302	0.0074	0.0085	0.0113	0.0028
R_4S_1	0.0173	0.0044	0.0130	0.0346	0.0088	0.0260	0.0130	0.0033	0.0097
S_2	0.0165	0.0082	0.0082	0.0330	0.0164	0.0164	0.0123	0.0062	0.0062
S_3	0.0158	0.0119	0.0039	0.0316	0.0238	0.0078	0.0118	0.0089	0.0029
R_5S_1	0.0215	0.0042	0.0086	0.0430	0.0084	0.0172	0.0161	0.0031	0.0064
S_2	0.0206	0.0082	0.0040	0.0412	0.0164	0.0080	0.0155	0.0062	0.0030
R_6S_1	0.0254	0.0042	0.0042	0.0508	0.0084	0.0084	0.0190	0.0031	0.0031

one interval between two successive weighings did not exceed 1.25 per cent, on the dry-weight basis. The average loss of transpirational water per culture during the intervals between successive weighings was, of course, very much lower than this and the loss was sustained during a very short period of time only. Thus the soil-moisture content of the cultures throughout the entire period of growth was maintained within very narrow variation limits.

The three sub-optimal series, one of the like optimal series, and the three supra-optimal series were conducted simultaneously during the 28-day period from November 13 to December 11, 1920 and these were then repeated during the period from March 10 to April 7, 1921. At the end of each period of growth the plants were harvested. The tops were dried at a temperature of about 102°C. and the dry weights obtained in the usual way. Owing to the great difficulty of accurately weighing roots that have grown in soil, the dry-weight yields of tops alone will here be considered.

EXPERIMENTAL DATA

The dry-weight values of tops are given in tables 3, 4, and 5. Each of the tables presents the data for the three series of cultures (one for each degree of soil moisture employed) comprised in a single one of the three groups. The culture numbers shown in the first column of each table define the positions which the cultures occupy in the series with respect to the triangular diagrams (6) employed to represent graphically the partial molecular concentrations and the molecular salt proportions of the solutions added to the soil-cultures to produce the required initial soil-moisture. Since the triple series of cultures in each group was repeated, the data in the tables represent averages of the yield-values obtained from corresponding cultures of like series conducted during different time-periods. The first column in each section of the tables representing the data for a single series, gives the average absolute yield-values in grams while the second column gives the average dry weight of tops relative to the corresponding weight of culture R_1 C_1 taken as 1.00. The relative data represent the values obtained by averaging the relative yield-values from corresponding cultures of like series conducted during different time-periods. These are, therefore, averages of two or more ratios and not the ratios of averages, which accounts for the fact that the relative values given in the tables do not always bear exactly the same relation to one another as do the absolute yield values.

As indicated in table 1, the optimal series in the three groups of cultures were identical. As previously stated, therefore, a single series sufficed to furnish the data for the optimal series in each of the three groups of cultures conducted simultaneously. This accounts for the fact that the average data for the optimal series in groups I and II (tables 3 and 4) are alike. It will be observed, however, that the data for the optimal series in group III (table 5) are not the same as are those of the corresponding series in groups I and II since the series of these two groups were only once repeated while those of group III were twice repeated. The data in tables 3 and 4 thus represent average dry-weights from corresponding cultures of two like series while those in table 5 represent average dry-weights from corresponding cultures of three like series.

The average relative data for the cultures which produced the highest seven yields in each series are shown in bold-face type in the tables. These values taken from the proper columns of tables 3, 4, and 5 were plotted on the triangular diagrams shown in figures 1, 2, and 3, respectively, as was done in the earlier

publication (10) dealing with the relation of the moisture-content in sand-cultures to salt-balance for wheat plants and corresponding to the present work with buckwheat plants in soil-cultures. The shaded areas on these

TABLE 3

Average absolute and relative dry weights of buckwheat tops grown 28 days in soil cultures of group I to which were added nutrient solutions (all having an osmotic concentration value of approximately 1.75 atmospheres) in the proper amounts to produce a soil-moisture content of 30 per cent, 60 per cent, and 80 per cent in the cultures of the sub-optimal, optimal, and supra-optimal series, respectively

CULTURE NUMBER	DRY WEIGHTS (4 PLANTS)					
	Sub-optimal series, 30 per cent moisture		Optimal series, 60 per cent moisture		Supra-optimal series, 80 per cent moisture	
	Absolute	Relative to R_1C_1 as unity	Absolute	Relative to R_1C_1 as unity	Absolute	Relative to R_1C_1 as unity
	gm.		*gm.*		*gm.*	
R_1C_1	1.5690	1.00	2.0560	1.00	1.6297	1.00
C_2	1.9976	1.22	2.5179	1.19	2.3746	1.40
C_3	2.2424	1.38	2.6231	1.26	2.4892	1.46
C_4	2.2520	1.39	3.1569	1.53	2.5760	1.54
C_5	1.9819	1.19	3.2918	1.61	2.2452	1.31
C_6	2.0112	1.20	3.0663	1.42	2.1671	1.35
R_2C_1	1.2541	0.82	2.0655	1.07	1.6513	1.00
C_2	2.0513	1.20	2.3480	1.27	2.1439	1.26
C_3	1.9857	1.16	3.3113	1.58	2.4689	1.48
C_4	2.3186	1.32	3.1674	1.52	2.5505	1.55
C_5	2.2625	1.34	3.3878	1.60	2.5342	1.46
R_3C_1	1.5336	0.98	2.1167	1.17	1.5660	0.97
C_2	1.8676	1.14	2.4931	1.25	2.5581	1.50
C_3	1.9027	1.18	3.0160	1.55	2.2293	1.35
C_4	2.2863	1.33	3.3692	1.61	2.7488	1.63
R_4C_1	1.4102	0.90	2.0094	1.04	1.7790	1.11
C_2	1.8730	1.14	2.4301	1.19	1.6545	1.06
C_3	2.2431	1.35	2.7042	1.35	2.4897	1.40
R_5C_1	1.5447	0.98	1.9071	0.98	1.5825	1.00
C_2	1.8900	1.16	2.4248	1.27	1.8030	1.10
R_6C_1	1.6497	1.03	2.0310	1.10	1.5574	0.97
Check	0.8498	0.57	1.1010	0.56	0.4829	0.31

triangular diagrams show the distribution in the series of the seven high-yielding cultures (upper one-third) only, since medium and low yields are of little interest in this connection. The positions of the cultures which produced the maximum yields in their respective series are marked with circles.

The three triangular diagrams showing graphically the distribution of the high-yielding cultures in the sub-optimal, optimal and supra-optimal series of any one of the three groups of cultures are brought together in a single

TABLE 4

Average absolute and relative dry weights of buckwheat tops grown 28 days in soil cultures of group II to which were added nutrient solutions (all having an osmotic concentration value of approximately 1.75 atmospheres) in proper amounts to produce a soil-moisture content of 30 per cent, 60 per cent, and 80 per cent in the cultures of the sub-optimal optimal, and supra-optimal series, respectively

CULTURE NUMBER	DRY WEICHTS (4 PLANTS)					
	Sub-optimal series, 30 per cent moisture.		Optimal series, 60 per cent moisture		Supra-optimal series, 80 per cent moisture	
	Absolute	Relative to R_1C_1 as unity	Absolute	Relative to R_1C_1 as unity	Absolute	Relative to R_1C_1 as unity
	gm.		*gm.*		*gm.*	
R_2C_1	1.3735	1.00	2.0560	1.00	2.1427	1.00
C_2	1.6917	1.21	2.5179	1.19	2.0607	1.00
C_3	1.6824	1.21	2.6231	1.26	2.4264	1.10
C_4	1.7928	1.22	3.1569	1.53	2.4070	1.17
C_5	2.0667	1.47	3.2918	1.61	1.8975	0.82
C_6	1.9132	1.27	3.0663	1.42	2.4261	1.15
R_2C_1	1.2926	0.96	2.0655	1.07	2.0307	0.99
C_2	1.6201	1.15	2.3480	1.27	2.2098	1.06
C_3	1.8601	1.30	3.3113	1.58	2.4720	1.21
C_4	1.9859	1.33	3.1673	1.52	3.0407	1.36
C_5	1.8811	1.31	3.3878	1.60	2.4330	1.23
R_3C_1	1.3002	0.94	2.1167	1.17	1.8600	0.93
C_2	1.6513	1.18	2.4931	1.25	2.0888	0.98
C_3	1.4628	1.05	3.0160	1.55	2.6455	1.30
C_4	1.9858	1.39	3.3692	1.61	2.6919	1.20
R_4C_1	1.3992	1.04	2.0094	1.04	1.8895	1.00
C_2	1.6309	1.15	2.4301	1.19	2.1084	1.12
C_3	1.7092	1.19	2.7042	1.35	1.9671	0.99
R_5C_1	1.4511	1.06	1.9071	0.98	1.7352	0.95
C_2	1.7836	1.26	2.4248	1.27	2.0095	1.08
R_6C_1	1.2687	0.92	2.0310	1.10	1.6023	0.78
Check	0.8455	0.57	1.1010	0.56	0.5953	0.35

figure for ready comparison. The three series in each group will be compared separately with respect to high yield-values and will then be considered in connection with the corresponding series in the other groups.

Group I

The method by which the required soil-moisture in the cultures of this group was created has already been described together with the experimental condition of the cultures at the beginning of the growth period. As shown in

TABLE 5

Absolute and relative dry weights of buckwheat tops grown 28 days in soil cultures of group III to which were added nutrient solutions, having total osmotic concentrations values of approximately 3.50 atmospheres in the sub-optimal 1.75 atmospheres in the optimal and 1.31 atmospheres in the supra-optimal series, in proper amounts to produce a soil-moisture content of 30 per cent, 60 per cent, and 80 per cent in the cultures of the three series, respectively

CULTURE NUMBER	DRY WEIGHTS (4 PLANTS)					
	Series A, 30 per cent moisture		Series B, 60 per cent moisture		Series C, 80 per cent moisture	
	Absolute	Relative to R_1C_1 as unity	Absolute	Relative to R_1C_1 as unity	Absolute	Relative to R_1C_1 as unity
	gm.		*gm.*		*gm.*	
R_1C_1	1.1615	1.00	1.1415	1.00	0.9790	1.00
C_2	1.2737	1.10	1.2600	1.11	1.1887	1.21
C_3	1.0305	0.88	1.3668	1.20	0.9008	0.92
C_4	1.1675	1.00	1.6954	1.49	1.0413	1.07
C_5	1.1160	0.95	1.7920	1.60	1.1167	1.14
C_6	1.1430	0.98	1.4160	1.24	1.1612	1.19
R_2C_1	1.1510	0.99	1.3729	1.20	0.9468	0.95
C_2	1.2707	1.09	1.4972	1.30	1.1113	1.14
C_3	1.1846	1.02	1.6608	1.48	1.0913	1.12
C_4	0.9748	0.82	1.6636	1.48	0.9778	1.00
C_5	1.2633	1.09	1.6962	1.49	0.9384	0.95
R_3C_1	1.1388	0.97	1.6328	1.45	0.9722	1.00
C_2	1.2380	1.07	1.4750	1.31	1.0060	1.03
C_3	1.3782	1.19	2.0045	1.75	1.2420	1.17
C_4	1.3060	1.13	1.7174	1.51	1.0315	1.06
R_4C_1	0.9255	0.77	1.3276	1.16	0.9727	1.00
C_2	1.2210	1.05	1.3770	1.20	1.3420	1.38
C_3	1.0995	0.93	1.6085	1.41	1.0970	1.12
R_5C_1	1.0454	0.90	1.2729	1.10	0.9845	1.01
C_2	1.5016	1.29	1.6372	1.45	1.2725	1.31
R_6C_1	1.4634	1.26	1.5253	1.34	1.0808	1.12
Check	0.7007	0.60	0.7926	0.64	0.4576	0.46

table 1, the amounts of soil used per culture in the different series were made inversely proportional to the required soil-moisture so that, when equal amounts of the same solution were added to the proper amounts of soil to

produce the required soil-moisture, the total salts per culture in corresponding cultures of the three series were also equal throughout but the total salts per unit volume of soil were directly proportional to the soil-moisture; that is, the total salts added were present in the proportions of 3:6:8 in the corresponding cultures of the sub-optimal, optimal, and supra-optimal series, respectively.

Inspection of the data in table 3 and a comparison of the triangular diagrams in figure 1 show at once that there is a marked degree of similarity between the three series comprised in this group with respect to the positions in the series of the cultures which produced high yields. The areas showing the highest seven yields for each of the three series occupy the same general region at the lower right on the triangular diagrams. Out of the group of cultures in each series which produced the highest seven yields, four are corresponding cultures of the three series and are included in the areas of high yields on each of the three diagrams. These cultures are R_1C_4, R_2C_4, R_2C_5, and R_3C_4. Culture R_1C_3 appears in the area of high yields on the diagrams of the sub-optimal and supra-optimal series but is not included in this area on the diagram of the optimal series. Likewise culture R_2C_3 is included in the area of high yields on the diagram of the optimal and supra-optimal series but is not included in this area on the diagram of the sub-optimal series.

The maximum yield of the sub-optimal series was produced by culture R_1C_4, which, however, did not correspond to the culture giving the highest dry weight in either of the other two series of this group. The maximum yields obtained from the optimal and supra-optimal series were produced by corresponding cultures, each of the cultures having the number R_3C_4 in its respective series. In the optimal series, however, cultures R_1C_5 and R_3C_4 show the same relative value. Each of these cultures is marked with a circle on the diagrams representing the series.

It is thus at once apparent that, under the conditions to which the cultures of this group were subjected, the fertilizer balance for good growth was not materially altered by the rather pronounced differences in the moisture-content of the cultures. This follows from the fact that the areas of high yields on the triangular diagrams representing the three series occupy the same general region at the lower right of the diagrams, four out of the highest seven yields in each series being produced by corresponding cultures. The conclusion is further supported by the fact that the maximum relative yield in the optimal and supra-optimal series was produced by culture R_3C_4 which was also included in the area of high yields in the sub-optimal series, although the maximum relative yield in this series was produced by another culture (R_1C_4).

The average absolute yield-values of the three series taken from the columns of table 3 were arranged in the descending order of the values for the optimal series. These values were then plotted as ordinates to form the graphs of figure 2 in which the culture numbers represent the abscissas.

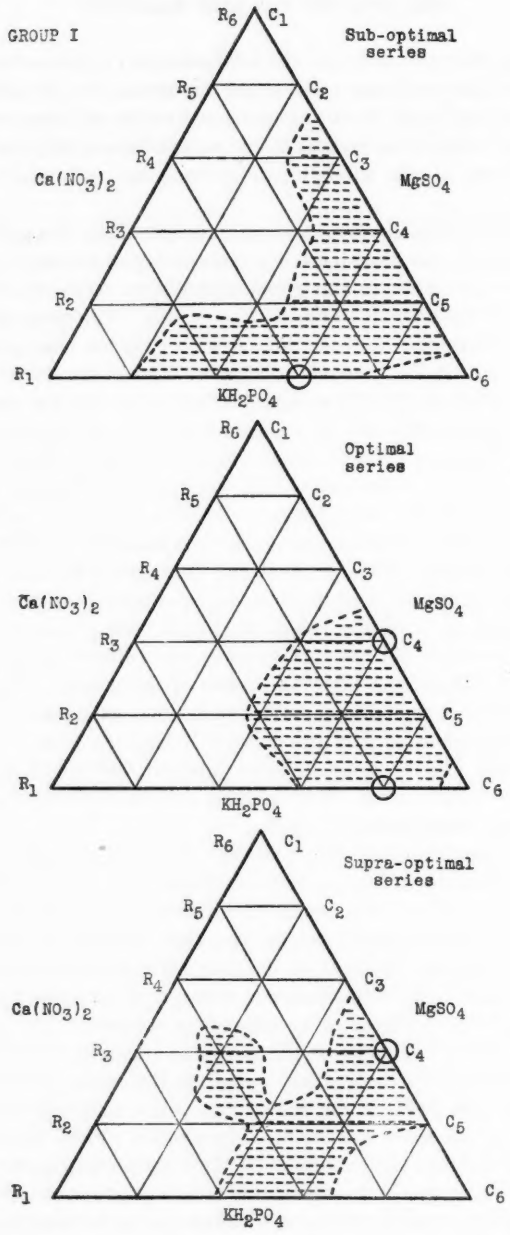

FIG. 1. DISTRIBUTION OF CULTURES PRODUCING THE HIGHEST SEVEN YIELDS OF BUCKWHEAT TOPS IN EACH SERIES OF GROUP I

The cultures giving maximum yields are marked with circles

The three graphs of figure 2 all agree in a general way in showing a gradual downward slope to the right. This indicates, of course, that the proportions of the fertilizer constituents designated by the culture numbers, in passing from left to the right, have a progressively less efficient balance for the growth of buckwheat in the particular soil employed. The graphs representing the sub-optimal and supra-optimal series (30 per cent and 80 per cent soil-moisture, respectively) are, of course, irregular and while there is a tendency toward parallelism between these two graphs in the upper half of their course they are not at all parallel to the graph of the optimal series.

The graph representing the optimal series in which the cultures had a medium soil-moisture content lies considerably above the other two graphs. Not a single culture of this series is surpassed in yield by a corresponding

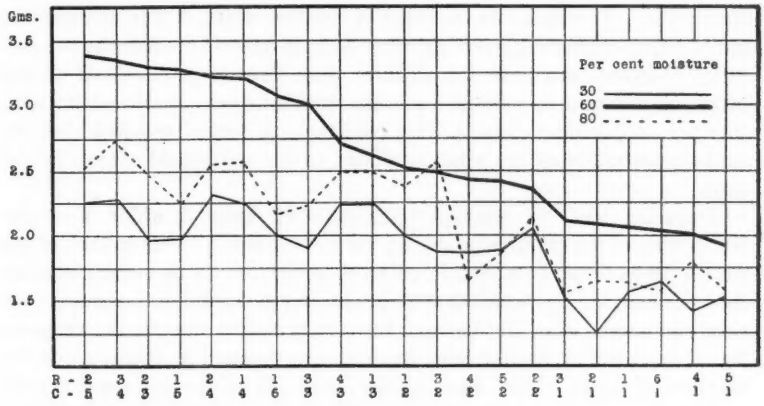

FIG. 2. AVERAGE ACTUAL YIELDS OF BUCKWHEAT TOPS FOR LOW, MEDIUM, AND HIGH SOIL-MOISTURE (SUB-OPTIMAL, OPTIMAL, AND SUPRA-OPTOMAL SERIES, RESPECTIVELY) OF THE CULTURES OF GROUP I

culture of the sub-optimal series and only one by the corresponding culture (R_3C_2) of the supra-optimal. It is to be observed also that the graph representing the supra-optimal series lies above that of the sub-optimal series throughout nearly its entire length, the yields from only three cultures of the former being inferior to the yields from the corresponding cultures of the latter.

The maximum average absolute yield from the optimal series is 46 per cent higher than that from the sub-optimal and 25 per cent higher than that from the supra-optimal, while the average of the highest seven yields from the optimal series is 45 per cent higher than the corresponding yield from the sup-optimal series and 27 per cent higher than that from the supra-optimal. The superiority of the yields from the cultures of the optimal series over those from the sub-optimal and supra-optimal is thus seen to be quite pronounced.

From the foregoing facts and from the evidence to be presented in connection with the consideration of groups II and III, it is apparent that this superiority of the yields from the cultures of the optimal series is the direct result of more favorable moisture conditions for growth.

In this connection it is to be emphasized that, in general, the influence upon the growth rates, as indicated by yield values, of such differences in soil-moisture content as existed between the cultures of the diffreent series is quite as pronounced as is the influence of the variations in the proportions of the fertilizer constituents as these occur throughout each of the three series.

Group II

In this group, equal amounts of soil were used for all the cultures of the three series. Therefore, the amounts of solution which it was necessary to add to corresponding cultures of the three series in order to produce the required initial moisture-content of the cultures were directly proportional to the initial soil-moisture, as were then also the total salts per culture and the total salts per unit-volume of soil. This condition, of course, required that the total concentration of the solutions added to the soil should always be the same.

Comparing now the triangular diagrams of figure 3 which show the distribution of the cultures producing the highest seven yields in each of the three series as shown in table 4, it will be observed that the agreement between the areas marking the positions of these cultures in the different series is even more pronounced than that between the corresponding areas on the diagrams (fig. 1) representing the series of the preceding group. As indicated on the diagrams of figure 3, the areas of high yields all occupy the same general region at the lower right of the triangles. Five cultures of those which produced the highest seven yields in each series are corresponding cultures and appear in the areas of high yields on each diagram. These cultures are R_1C_4, R_2C_3, R_2C_4, R_2C_5, and R_3C_4. It will be observed also that culture R_1C_5 is included in the area of high yields on the diagram of the sub-optimal series and optimal series but not on that of the supra-optimal series, while culture R_1C_6 appears in the shaded area on the diagram of the sub-optimal and supra-optimal series but not on that of the optimal. Similarly culture R_3C_3 is included in the area of high yields on the diagram of the optimal and supra-optimal series but does not appear in this area on the diagram of the sub-optimal.

The maximum yields in the three series of this group were not produced by corresponding cultures although culture R_1C_5 which produced the maximum relative yield in the sub-optimal series corresponds to the culture which produced a secondary maximum yield in the optimal series. The relative yields from two cultures (R_1C_5 and R_3C_4) of this series show equal values. The maximum yield from the supra-optimal series is indicated for culture R_2C_4.

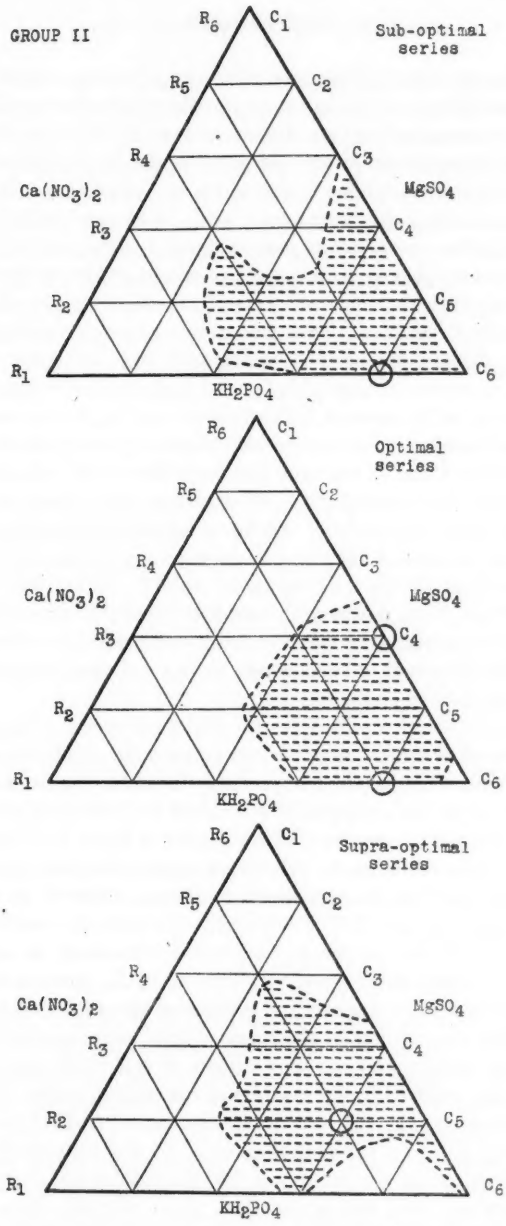

FIG. 3. DISTRIBUTION OF CULTURES PRODUCING THE HIGHEST SEVEN YIELDS OF BUCKWHEAT TOPS IN EACH SERIES OF GROUP II

The cultures giving maximum yields are marked with circles

The diagrams of figure 3, like those of figure 1, show very clearly that there is no significant shifting of the balance of fertilizer constituents characterizing good growth in changing from a soil-moisture content which was considerably below that of the optimum to one above the optimum. This is true for the sets of experimental conditions under which the cultures of this group and those of the preceding group were carried out. A comparison of the diagrams of figure 3 with the corresponding ones of figure 1 shows that these diagrams are in very close agreement with respect to the positions on the diagrams of the areas of high yields, since all occupy somewhat similar regions at the lower right of the triangles. This general agreement is emphasized by the fact that four cultures among those which produced the highest seven yields in each of the six series represented in figures 1 and 3 are corresponding cultures and are included in the areas of high yields on each of the six triangular diagrams. In this connection it is to be noted that in the preparation of the soil cultures of groups I and II the total concentration of the solutions added to the soil to create the required initial soil-moisture was always the same (1.75 atm.) and the total salts per unit volume of soil in corresponding cultures of the three series in each of the two groups were always directly proportional to the soil-moisture content, as shown in table 1. Alteration of these two important factors (since it was not possible to alter the one without altering the other) produced markedly different results with respect to the salt balance required for good growth of buckwheat in the soil used, as will appear in considering the data of group III.

The average absolute yield-values for the three series of group II taken from the columns of table 4 were plotted to form the graphs shown in figure 4. These graphs were prepared in precisely the same manner as were those (fig. 2) representing the corresponding series in the preceding group. It will be observed that the arrangement of the graphs of figure 4 is quite similar to that of the graphs of figure 2. The graph representing the yields from the optimal series with medium soil moisture is again seen to lie considerably above the other two graphs. Thus under the cultural conditions defined at the beginning of this section and expressed numerically in table 1, every culture of the optimal series except one (culture R_1C_1) shows a marked superiority in yield over the corresponding cultures of the other two series in spite of the fact that the cultures of the supra-optimal series received a total salt application per culture and per unit volume of soil which was considerably higher than that received by the cultures of the optimal series. On the other band, the cultures of the sub-optimal series received a total salt application which was only half as great as that received by the cultures of the optimal series. However, when the cultures of the sub-optimal and of the supra-optimal series received total salt applications which equaled those received by the cultures of the optimal series the relation between this series and the other two, with respect to the yields produced, was not materially altered as is clearly shown by a comparison of the graphs of figures 2, 4, and 6.

The superiority of the yields from the optimal series over those from the other two series is emphasized by the fact that the maximum yield from this series was 63 per cent above that of the sub-optimal and 11 per cent higher than that of the supra-optimal, while the average of the highest seven yields from the optimal series was 69 per cent and 25 per cent higher than the corresponding yields of the sub-optimal and supra-optimal series, respectively.

The graph representing the supra-optimal series (fig. 4) lies considerably above that of the sub-optimal throughout almost its entire length, only a single culture (R_1C_5) of the former series being surpassed in yield by the corresponding culture of the latter. Thus the relation between these two graphs is quite similar to that exhibited by the graphs representing the corresponding series of the preceding group (fig. 2).

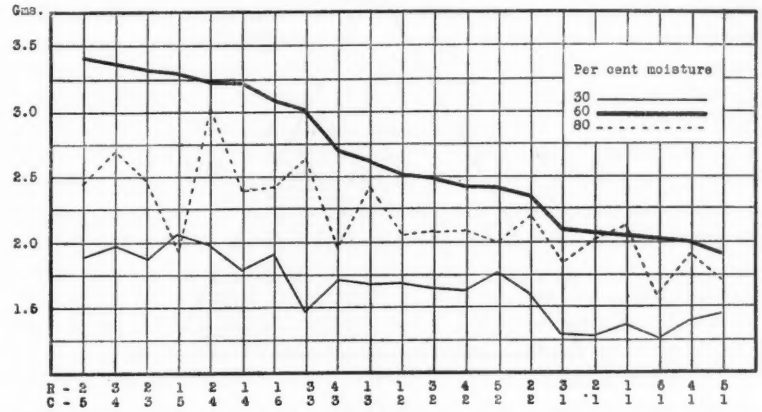

FIG. 4. AVERAGE ACTUAL YIELDS OF BUCKWHEAT TOPS FOR LOW, MEDIUM, AND HIGH SOIL-MOISTURE (SUB-OPTIMAL, OPTIMAL, AND SUPRA-OPTIMAL SERIES, RESPECTIVELY) OF THE CULTURES OF GROUP II

Group III

In this group, as in group II, equal amounts of soil were used in all the cultures and the amounts of solution added to the soil cultures of the three series in order to produce the required initial soil-moisture were of necessity again made directly proportional to the moisture-content of the cultures. The proportions were as 3:6:8 in the cultures of the sub-optimal, optimal, and supra-optimal series, respectively. Although the salt proportions of the solutions added to corresponding cultures were always the same it is important to note that the total salt concentrations of the solutions differed widely since they were inversely proportional to the soil-moisture content. The solutions added to the cultures of the sub-optimal, optimal, and supra-optimal series had total osmotic concentration values of 3.5. 1.75, and 1.31 atmospheres,

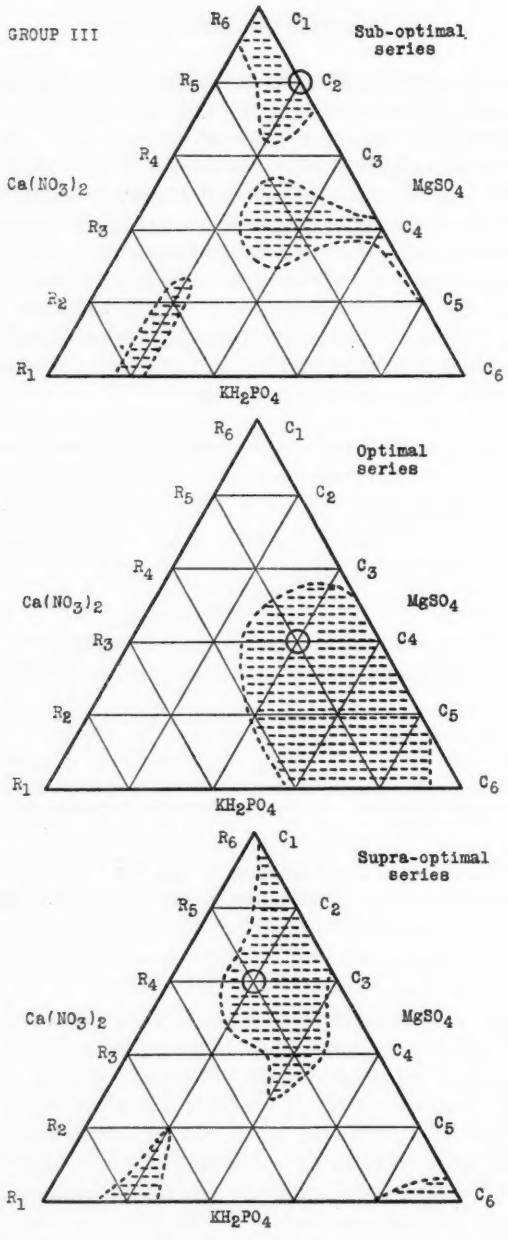

FIG. 5. DISTRIBUTION OF CULTURES PRODUCING THE HIGHEST SEVEN YIELDS OF BUCKWHEAT TOPS IN EACH SERIES OF GROUP III

The cultures giving maximum yields are marked with circles

respectively. The total salts per culture and the total salts per unit volume of soil in corresponding cultures were, therefore, equal throughout as indicated by the relative data in table 1.

The triangular diagrams graphically representing the three series of this group are shown in figure 5. It will be observed that there is scarcely any agreement, with respect to the areas marking high yields, between the diagrams of the optimal series and those of the other two series. On the diagrams of the sub-optimal and supra-optimal series the high yields are included in small detached areas nor do these occupy the same general region at the lower right on the diagrams as do the areas of high yields of all the series comprised in the preceding groups (figures 1 and 3) and that of the optimal series in the present group. Only a single culture (R_3C_3) of those which produced the highest seven yields in the respective series appears in the area marking these on the diagram of each of the three series. However, out of the highest seven yields from the sub-optimal series and from the supra-optimal series four were produced by corresponding cultures and these are shown in the detached areas of high yields on the diagrams representing these two series, but there is little similarity between the areas of high yields on the two diagrams. The main point of agreement lies in the small area at the lower left on each triangle embracing the two cultures R_1C_2 and R_2C_2.

In the sub-optimal series the maximum relative dry weight yield was produced by culture R_5C_2, in the optimal series by culture R_3C_3, and in the supra-optimal series by culture R_4C_2.

It is thus evident that the fertilizer balance characterizing the cultures which produced high yields in all the series of the preceding groups and in the optimal series of the present group is markedly different from that characterizing the high yielding cultures in either the sub-optimal or the supra-optimal series of this group. This alteration of the salt balance characterizing high yields in the sub-optimal and supra-optimal series may be attributed directly to the difference in the total concentration of the solutions added to the cultures of the different series to produce the required initial soil-moisture. The solutions added to the cultures of the sub-optimal, optimal, and supra-optimal series had total osmotic concentration values of approximately 3.5 1.75, and 1.31 atmospheres, respectively, but the total salts per culture as well as the total salts per unit volume of soil were equal throughout. That this difference in the fertilizer balance required for good growth is not due to the variations in the moisture-content of the cultures of the different series is clearly brought out by the fact that, as shown in table 1, the solutions added to the cultures of the series in groups I and II, as well as to those in the optimal series of group III, all had approximately the same total osmotic concentration value (1.75 atm.), and that in the series in question, seven in all, no significant alteration in the salt balance characterizing the cultures which produced high yields was observed with change from the highest to the lowest soil-moisture content. Pronounced shifting of the balance of salt proportions characterizing

good growth in the soil here used occurred only with notable differences in the total concentrations of the solutions employed to produce the required initial soil-moisture, and such differences in total salt concentration existed only in the solutions added to the cultures of the sub-optimal and supra-optimal series of group III, the triangular diagrams of which are shown in figure 5. In this connection it has been pointed out by Gile (3), McCool (8, p. 113–170), Tottingham (11) Shive (9), McCall (7), Ayres (1), and others that the balance of salt proportions required for plant growth (good, medium, or poor) is not at all independent of the total salt concentration of the medium in which the plants are rooted, a conclusion which is supported by the present work.

The absolute average dry-weight yields from the series of group III, as given in table 5, are presented graphically in figure 6 in the same manner as were those from the series of the preceding groups. The graph of the optimal series again lies above that of the supra-optimal throughout but its lowest two values are slightly surpassed by the corresponding values of the sub-optimal graph. With the exception of the two yield-values just mentioned, the cultures of the optimal series exhibit much higher average dry weights than do those of the other two series. This relation is quite similar to that shown to exist between the corresponding series of the preceding groups.

The maximum yield from the optimal series was 33 per cent higher than that from the sub-optimal and 49 per cent above that of the supra-optimal. The average of the highest seven yields from the optimal series was 22 per cent and 45 per cent higher than the corresponding yields from the sub-optimal and supra-optimal series, respectively.

Thus in the present group, as in the preceding ones, the differences in yield resulting from differences of soil-moisture in corresponding cultures are even more pronounced than are differences in yield which may be attributed to variations in the proportions of the fertilizer constituents throughout each series. This emphasizes the point to which attention was given in the earlier publication (10) that in all soil or sand culture studies it is of primary importance to maintain the moisture-conditions of the substratum in which the plants are grown within very narrow variation limits where the influence of other factors under investigation, such as the kind, total concentration, and proportions of fertilizer constituents, is being measured by the growth rates of the plants.

The graph of the sub-optimal series lies above that of the supra-optimal series throughout most of its length. Only three values of the former are surpassed by the corresponding values of the latter. The relation between these two graphs is, therefore, the reverse of that exhibited by the graphs of the corresponding series in both groups I and II (figures 2 and 4). This reversed relation between the graphs in question indicates that, in pot-cultures such as were here used, with any given set of fertilizer constituents, the total salts per unit-volume of soil in which the plants are grown bear a more important relation to the growth rates of the plants than do the total salts per

culture. This appears from the fact that in the sub-optimal and supra-optimal series of group I the total salts per culture were present in corresponding cultures in the ratio of 1:1, while in group II this ratio was 1.00:2.66, yet the relation between the graphs representing the two series in each group are quite similar as a comparison of the graphs in figures 2 and 4 will show. Nor did differences in the amounts of soil used per culture appear to have any influence upon this relation. On the other hand, the total salts per unit-volume of soil in corresponding cultures of the sub-optimal and supra-optimal series in both groups I and II were present in the ratio of 1.00:2.66, while in group III this ratio was 1:1. Thus, with the change in the total salts per unit-volume of soil in corresponding cultures, the relation between the graphs representing the two series suffered a complete reversal, as is shown by a

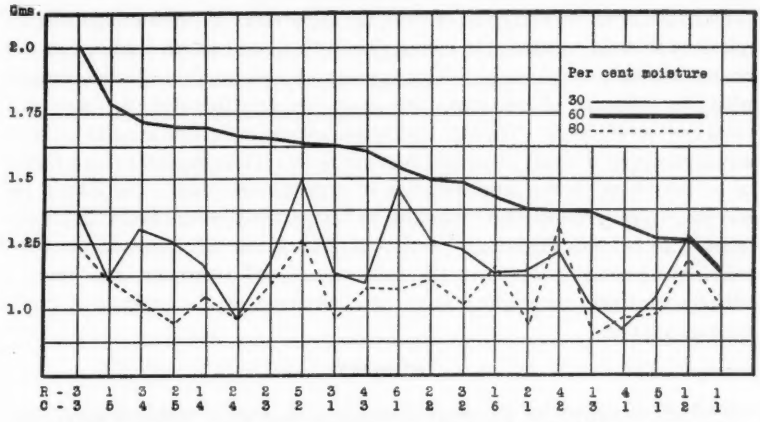

FIG. 6. AVERAGE ACTUAL YIELDS OF BUCKWHEAT TOPS, FOR LOW, MEDIUM, AND HIGH SOIL-MOISTURE (SUB-OPTIMAL, OPTIMAL, AND SUPRA-OPTIMAL SERIES, RESPECTIVELY) OF THE CULTURES OF GROUP III

comparison of the graphs in figure 6 with those in figures 2 and 4, while a like change in the total salts per culture had no apparent influence upon the relation between the graphs representing the two series. It is to be observed, of course, that any alteration in the ratio of total salts per unit-volume of soil in corresponding cultures of the different series above noted involved also a corresponding change in the total concentrations of the solutions with which the initial salt applications were supplied to the soil.

A comparison of the three sets of graphs (figures 2, 4, and 6) representing the average actual yields shows that the highest seven yields from the series in which the cultures had an approximately optimum soil-moisture, were always greatly superior to the corresponding yields from the series in which the cultures had a soil-moisture content which was either above or below that of the optimum, regardless of the different experimental conditions to which

the cultures were subjected. This relation was not altered by the use of larger or smaller amounts of soil per culture than that used for the cultures of the optimal series, by higher or lower total concentrations of the solutions added to the soil-cultures to create the required initial moisture-content, nor by higher or lower salt applications per culture or per unit-volume of soil. It is thus to be expected that any fertilizer mixture in which the salt proportions are properly balanced for the good growth of a given species in a given soil can not be most efficiently utilized by the plants if the moisture-content of the substratum is either too high or too low, nor can fertilizer treatment alone entirely counteract the retarding influence upon plant growth of unfavorable moisture-conditions. The maximum plant-producing value of any fertilizer mixture can only be attained when the moisture-condition of the substratum is at the optimum for plant growth.

From the experimental point of view, the importance of considering moisture relations in solid substrata in connection with plant-culture studies can not be too strongly emphasized. This applies as well to field studies dealing with the influence of soil treatment upon the growth rates of plants and upon crop production. The fact that soil-moisture in the field is quite variable and exceedingly difficult to control does not render it less important as a factor to be considered in the interpretation of experimental data. As Harris (4) has pointed out, soil-moisture has always been a troublesome factor in experiments with soils and crops and the effect of unavoidable differences in moisture-conditions frequently obscures the influence of soil treatment and renders entirely worthless data which have been obtained at the expense of much time and labor.

SUMMARY

A study was made of the effect of different degrees of moisture upon physiological salt balance as this affected the growth of buckwheat plants in soil cultures. Three different degrees of soil-moisture were maintained: 30 per cent, 60 per cent, and 80 per cent based on the maximum water-retaining capacity of the soil used. Tests were made with 21 different sets of salt proportions of the three salts KH_2PO_4, $Ca(NO_3)_2$, and $MgSO_4$ supplied to the air-dry soil in the solution form. The solutions were added to the soil in the proper amounts to create the required initial soil-moisture. The methods by which this was accomplished are described. Nine series, each comprising 21 cultures, divided into three groups of three series each were conducted simultaneously and repeated. The cultures were weighed and the water loss by transpiration was restored daily throughout the growth period. A brief summary of the main results derived from the experimental data follows:

1. The balance of salt proportions which characterized the cultures producing high yields was not materially altered by variations in the degrees of soil-moisture when the total osmotic concentration values of the solutions added to the soil cultures to produce the required initial soil-moisture were

approximately constant. In general the salt proportions which produced high yields of tops with the lowest degree of soil-moisture gave high yields also with the medium and the highest degree of moisture in the respective series.

2. Pronounced shifting of the balance of salt proportions characterizing the cultures which produced high yields occurred only with marked variations in the total concentration of the solutions added to the soil.

3. The yield-differences resulting from variations in the degrees of soil-moisture are quite as pronounced as are yield differences which may be attributed to variations in the proportions of the fertilizer constituents with constant soil-moisture.

4. The retarding influence of unfavorable soil-moisture conditions upon the rate of growth of the plants can not be counteracted by fertilizer treatment alone. High yields from cultures with medium soil-moisture (60 per cent on the basis of maximum waterholding capacity of the soil) were always greatly superior to the corresponding yields from the cultures with either high or low soil-moisture regardless of experimental methods or conditions to which the cultures were subjected.

5. The salts comprised in a fertilizer mixture can not be efficiently utilized by the plants under unfavorable moisture-conditions. The maximum plant-producing value of any fertilizer mixture can only be attained when the moisture-conditions of the substratum are at the optimum for plant growth.

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